VOLUME 23, 1961/62, No. 7 pp. 189-220 Published 19th April 1962

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

OPTO-ELECTRONICS

by G. DIEMER *).

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*On 6th October 1961 Dr. G. Diemer delivered an address under the above title upon his inauguration as professor extraordinary at the Technische Hogeschool, Eindhoven. The text is reproduced below more or less verbatim. In accordance with custom, the speaker made no use of such visual aids as drawings or formulae written on the blackboard or of slides. Professor Diemer's deliberate and extensive use of verbal imagery, however, more than made up for their lack. For this reason the editors refrained from supplementing the text with figures. An interlude, in which an opto-electronic experiment was demonstrated with the aid of a burning cigar, has been omitted, but we felt we should not withhold from our readers another interlude in which the speaker expatiates on the function of language and imagery. For the rest, the style of this speech will doubtless reveal the affinity of spirit between the speaker and other authors such as G. Remedi **) who have previously graced the columns of our journal.*

My aim in the following considerations is to tell you something about my particular pursuit, opto-electronics — a small domain in the territory of the technical sciences. I shall tour the ground with you and try to describe the state of its cultivation. Now and then we shall take a look at the larger surrounding fields of physics and technology so that we can see our own land in its right proportions.

The nature of our work resembles that of gardeners and nurserymen; certain shrubs are planted and tended with care, others are pruned back or even eradicated. Eagerly and patiently the cultivator seeks for new varieties, and the skilled worker feels content when the fruits of his labour are appreciated by others. Let me first try to make you acquainted with some of the more proficient cultivators that we shall meet on our tour and with a few of the more outstanding plants that embellish our garden.

That delicate plant, which has spread into the farthest corners of our estate, is called Planck's constant. It bears the name of the famous grower who, with his deep ploughing, has permanently changed the structure of our land. This species of moss, whose spores are also to be found nearly everywhere in the "hortus physicus", is known briefly as "electron". Personally I would rather it had been named after "old J.J.", who was the first to grow this species in a pure culture. Over there, in that ancient corner, you can see a couple of stout Newton oaks — still massive, although Albert with his youthful zest lopped them a bit about half a century ago when he put up that trim hedge of relativity privet. Albert left untouched, however, those tall and graceful Maxwell beeches which, majestically mature, still tower above nearly everything grown here. That row of waving Schrödinger poplars was planted only a few decades ago. They shot up quickly, and now their roots are threatening the base of Albert's hedge. Some of our soil experts are rather worried about this, but otherwise we gardeners like the shade from all these trees and we feel safe on this protected estate. As long as we are kept usefully and agreeably busy in our own garden, tending, planting and cultivating, I think we may rightly regard ours as a dignified and worthwhile occupation. Unfortunately there are some who, in their enthusiasm for the job, cannot resist the temptation to spread their plants by single-crop cultivation all over the earth's surface, where, outside their own domain, they tend — much to the alarm of their specialized growers — to degenerate into rank weeds. Unthinkingly they often stamp with heavy boots over the carefully laid flowerbeds of others, and even I have to tread cautiously here lest I step over the bounds of my own ground.

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*) Philips Research Laboratories, Eindhoven.

**) G. Remedi, Science goes to the fair, Philips tech. Rev. 17, 362-368, 1955/56.

I admit that I have sustained my metaphor longer than is customary in discourses of this kind, and I can imagine that some of you will be wondering uneasily whether you have strayed into a school of horticulture instead of an institute of technology. But what is metaphor? All language is metaphor, even that of science and technology. There is only a difference in the degree of lameness, and to escape the accusation that my metaphor no longer has any leg to stand on, I promise that from now on I shall deal in more concrete terms with the phenomena of light and colour observable in my field of study.

Opto-electronics has become established in the specialist literature of recent years as the term denoting that part of the physics and technology of the solid state which is concerned with the interaction of light and electrons in matter. More particularly we can distinguish here two groups of phenomena which are in a certain sense complementary: on the one hand there is the change that takes place in the electrical properties of some semiconductors and insulators when they are irradiated by light, and on the other there is the change in the optical properties of these substances when they are subjected to the action of electric or magnetic energy. If we disregard for a moment the third form of energy — thermal energy or heat — which plays an accompanying or fundamental part in nearly all solid-state phenomena, these two complementary groups, as defined, are distinct from two other closely related branches. These are: solid-state *electronics*, where both the energy supplied and the effects thereby produced are electric or magnetic in nature, and solid-state *spectroscopy*, where the energy supplied and the effects are both of an optical nature.

The branches mentioned are in practice — and fortunately — not rigorously distinct from one another, and it is precisely the give and take between them that often leads to the discovery of interesting new effects or to their practical application. In the case of fluorescence, for example — a purely optical effect where light phenomena are produced by optical energy — the interaction of light and electrons in the solid is an essential intermediate stage in the process. The knowledge gained of these electronic processes has quite recently made it possible to generate, in what is called a "laser", a form of fluorescence where, unlike all other forms of light production hitherto known, the light waves are coherent, that is they are emitted in a regular rhythm. The underlying principle of this device is "stimulated emission", an effect that was known more than fifty years ago from the theoretical analysis of the laws of radiation and which has found practical application during the last ten years in the "maser" for generating and ampliying microwaves.

I shall confine myself here, however, to the two complementary fields of opto-electronics which I have mentioned. Where optical radiant energy results in a variation of electrical properties I shall speak, for the sake of brevity, of an r.e. effect (*r* for radiation, *e* for electricity), and, in the alternative case, of an e.r. effect. Here too, the phenomena involved are so multifarious that it will be wise to select from each field one representative effect for further discussion.

Let me first draw your attention to the r.e. effect called photoconduction. Certain solids, for example a cadmium sulphide crystal, which by nature contain very few freely mobile electrons, exhibit when illuminated a marked increase in their electric conductivity, proportional to the number of free charge carriers produced by the irradiation. The energy that enables the electrons to break out of their bound state is supplied by the light quanta or photons incident on the crystal — hence the term photoconduction. A photoconductor, then, may be regarded as an electric-current switch having a finite internal resistance, the mechanism being operated by the incident light signal. The efficiency of the operation can be expressed in terms of power gain, i.e. the ratio of the electric power that can be switched on and off by the crystal to the radiant power that must fall on the crystal for that purpose. The power gain of cadmium sulphide may have the surprisingly high value of many millions. Opto-electronic "straight" amplifiers can be built by combining such a sensitive r.e. element with an e.r. element. There are two ways in which this can be done.

In the (e.r. - r.e.) combination, where the coupling between the two elements is effected by radiation, the driving signal and the delivered power are both electrical, so that the whole can be regarded as an electrical amplifier. In the (r.e. - e.r.) combination the coupling is electrical and both the driving and delivered power are radiation signals. This makes it possible, therefore, to amplify radiation, and if many such combinations are stacked in the form of layers, image intensification can be achieved. However, as we shall see presently, the e.r. elements hitherto available convert electric energy into light with such poor efficiency that as far as this element alone is concerned we have to speak of attenuation instead of amplification. It is for that very reason that a high power gain in the photoconductor is of such exceptional importance for practical applications.

The requirements for achieving this high gain are: in the first place it must be possible to expose the substance to a strong electric field; next, the liberated charge carriers must have a high mobility and a long life in their free state, that is there must be a long interval of time between the moment of their liberation and their return to the bound state. As a result the switching on and off of the photoconductor is accompanied by a time lag that can never be shorter than the interval mentioned. Plainly, then, photoconductors that owe their high sensitivity to the longevity of the liberated electrons must possess an inherent response lag. In the case of cadmium sulphide the lag is of the order of 0.1 to 0.01 second; with the related cadmium selenide, switching times of about 1 millisecond are possible, but the gain here is correspondingly lower. As I have said, the poor efficiency of the e.r. elements at present available makes it necessary for the photoconductor to have a very high gain factor if the combination is to be effective. The requirements mentioned indicate the direction in which we should search for materials and preparation conditions that will supply us with sensitive and fast photoconductors. The search is important because if the switching speed can be increased the potential applications will be considerably widened.

In spite of their moderate switching speed these devices already have so many attractive aspects that it will certainly not be long before they are put to certain practical uses. One aspect is that switching by means of light signals offers opportunities of coupling and decoupling signals in ways that would be difficult to achieve in an entirely electrical circuit. This can be simply illustrated by pointing to the fact that, unlike electrical conductors, two light rays cause no short-circuit if they intersect. Another aspect is covered by the American coinage "molecular electronics": the opto-electronic circuits discussed here function by virtue of the properties of the substance itself which, to handle the signals as required, only needs to be supplied with electrodes to which a voltage is applied. Additional lumped coupling elements, such as capacitors, resistors and inductors, are not necessary, and this makes it quite possible to build a complete circuit in a very compact form by using simple layer structures on which more or less complicated electrode systems are impressed (e.g. by a printing technique). But further improvements are also to be expected in the field of e.r. elements, and I should now like to discuss their most important representative for practical purposes at the present time — the electroluminescent panel.

In a review article *) I once described the mechanism of the electroluminescent panel as follows: "The functioning of a luminous panel differs from other familiar kinds of luminescence, such as cathodoluminescence (as in television picture tubes) and photoluminescence (as in fluorescent lamps) only in the way in which the excitation of the solid substance takes place. In cathodoluminescence, excitation is brought about by bombardment with a beam of fast electrons which, in penetrating the substance, raise certain bound electrons to a higher energy state; the bound electrons are thereby rendered capable of emitting light quanta $h\nu$ (h = Planck's constant = 6.62×10^{-34} joule sec; ν = frequency of light = number of vibrations per second) on reverting to the ground state. In photoluminescence the same kind of excitation is caused to take place in the substance by its absorption of short-wave radiation, such as ultra-violet quanta, falling upon it. It seems that electroluminescence, as in a luminous panel, can best be understood by supposing that mobile electrons are present in the electroluminescent substance, that these electrons are able to acquire kinetic energy from the electric field and, when they have sufficient energy, are able to bring bound electrons in the crystal into an excited state by colliding with them (impact excitation)."

So much for the quotation. May I now assume that you know what we mean by electroluminescence? I can hardly expect it of the uninitiated among you, even though in writing this description an effort was made to use no more jargon than was necessary, and moreover the article went through the hands of a professional editor, experienced in the simple and clear exposition of scientific and technical information. I therefore propose to analyse this piece of prose and to comment on the statements it contains; in doing so I shall have the opportunity to say more about the background of our research and the methods employed.

By way of interlude I should like at this point to present some general observations on the language we use and on matters connected with it. This is a subject about which I feel strongly, and I do not want to let this chance go by without saying a few words about it in my own circle. The physicist busy with his daily work, with his thoughts, formulating ideas and talking to colleagues and associates, uses a language familiar to him, usually his mother tongue. In the style of the extract I have just cited, however, something emerges of the typical manner in which we tend to use language in our publications. Unlike our practice in daily discussions and contrary to what has really happened in the laboratory, our propensity in writing with our lavish use of the passive form and the "pluralis physicorum", is towards impersonal narration which is meant to suggest objectiveness. We thus humbly sacrifice our personality on the altar of "repeatability". But is language indeed merely a code system for communicating information?

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*) Philips tech. Rev. **19**, 1, 1957/58.

It has often been said that nothing is really repeatable. Indeed, the adoption of new ideas and concepts, originated by our great authoritative researchers, is essentially *un*repeatable. They influence the way of thinking of their contemporaries and later investigators to such an extent that if only for that reason science and technology pass through a non-repetitive process of historical evolution. Newton's concept of mass, Planck's constant, Bohr's model of the atom, Einstein's theory of relativity, they will always leave their traces in our soil, however much we go on ploughing and working the same ground. Even the language of science, the vehicle, stimulant and reflection of our scientific thinking, undergoes a directed non-repetitive process of growth. And if only because the postulation of new concepts, the formation of fresh imagery, is a creative process, just as all creative work springs more from imagination, intuition and courage than from reasoning, the body of the so-called exact sciences will always contain essentially non-rational elements. The genius of the great men of science in fact lies in a combination of the qualities I have mentioned; they are not afraid, in the face of the apparently irrefutable logic of the existing, rationally ordered data of experience, to say how they see and think about things. It was not logical of Planck to refrain from letting the energy of his "packets" of radiation go to zero when he was trying to explain the experimentally determined laws of radiation; it was illogical of Bohr to postulate that an electron circling in its orbit does not radiate. In technology we find clear recognition of the value of such non-rational factors in the practice of patent grants, where a true invention is expected to be based rather on an unexpected, surprising idea than on a conclusion arrived at by logical reasoning from existing data known from experience.

But there is more to it than that. For our research, our growing up into physicists and our work as such, take place less than ever before in ivory towers — in spite of our enforced seclusion in establishments from which the outside world is rather sternly excluded. They are bound by many threads of social and other human activities to life as a whole. In learning and making use of what we have learned, in determining the direction of our research and in attempting, as part of a group, to go farther in that direction — in all these stages language is more than merely a code system for communicating information.

In the beginning was the Word. Goethe's Faust, for me in many respects *the* representative of scientific investigators, hesitates at this text and, after reflection, writes down instead, one after the other: the meaning, the power, the deed! Going back over the train of our thoughts, however, I arrive at another beginning: the *image*, the remarkable capacity of the human mind to order the chaos of its impressions and perceptions into images and concepts. On this genesis of all thought, more conjurative than rational, depends the conveyance of language from mother to child and our ability to communicate our experiences and ideas and to receive those of others. I have found that learning to recognize and understand the non-rational elements in the physical sciences and technology has been a great help in advancing my development as a scientific investigator.

I should like to begin my discussion of the extract quoted on electroluminescence by commenting on the concept of luminescence.

Luminescence is a particular form of light emission for which the necessary energy is *not* supplied by heating. Fire, the candle flame, the incandescent gas mantle, the electric filament, and also the sun and the stars are all familiar forms of light sources whose ability to emit light derives from heating. The lightning flash, the glow from marine forms of life and from fireflies, neon signs, yellow sodium lighting from street lanterns, the light from fluorescent lamps and from television screens, Čerenkov radiation and also the light from the electroluminescent panel, on the contrary, are not due to heating and are therefore examples of luminescence.

Why do we place such emphasis in this definition on whether or not the generation of the light is of thermal origin? To me the most important reason is the wish to dissociate luminescence from the coarse mode of excitation that heating essentially is. As I remarked, we have known since Planck that light is emitted in discrete energy quanta of the magnitude $h\nu$, corresponding in the range of visible radiation to electron transitions or "jumps" of 2 or 3 volts. If we heat a solid we increase the thermal agitation energy of the ensemble of its atomic nuclei and electrons. The movements of the atomic nuclei and electrons are entirely random, however, and the energy that we can supply to the electrons in this way fluctuates around an average value which increases in direct proportion to the temperature. At the temperatures which available solids can withstand without all too quickly evaporating, this average energy is a lot lower than is needed for electron transitions of 2 or 3 volts. Only a few energetic outliers of the chaotic movements are able to produce an electron transition sufficient for a visible quantum to be emitted. Most of the transitions are too small and result in infra-red or heat radiation. The direct conversion of thermal energy into light is therefore just about as efficient as if we were to hurl a piano down the stairs in order to get a certain note out of it. With luminescence our aim is to learn the art of striking the right note.

To the physicist, however, luminescence is not merely the emission of visible radiation. *Electro*-luminescence, for example, encompasses radiation in the ultra-violet and infra-red as well as in the visible spectrum. Physically these radiations are closely related: for us they differ only in frequency, which is highest in the ultra-violet and lowest in the infra-red. The ease with which we physicists generalize concepts derived from the experience of the senses lends our research a flexibility that may sometimes sadly let down those who are eager to turn our inventions to practical use. The electroluminescent panel — in its simplest form a thin layer of zinc-sulphide paint coated on a base and provided with electrode layers to which the mains voltage is applied — was originally hailed as a potentially interesting flat light-source of extremely simple construction. When we found, however, that such panels were not so very suitable for the purposes of lighting — for rather fundamental reasons which I shall presently deal with — all we had to do was to shift the wavelength range up a bit in order to find an entirely different use for them, that is in the opto-electronic circuits already mentioned. For switching electric signals with the aid of radiation quanta it is evidently of no immediate consequence whether the radiation is visible or not, and it now turns out that the near infra-red offers the best compromise in regard to the speed and sensitivity of the circuit. To the physicist it is a small matter to vary the wavelength by hardly a factor of two, but the lighting engineer may feel that he is again being sold a pup.

Here in Eindhoven, under the smoke of the lamp factories, I can hardly avoid telling you something more about the reasons why we expect this "light-source of the future" to keep that name for the time being in a strictly literal sense. It is true that the luminous panel conforms to the definition given, in that the light emission is not due to heating, but that does not alter the fact that about 99% of the electrical energy supplied is converted into heat and only 1% into light. If we wanted to light a whole room with these panels, for instance by covering the walls and ceiling with them, we should discover that our "luminous tiles" had turned our room into something like a tiled stove.

The fact that low efficiency is a typical feature of an electroluminescent panel is bound up with the mechanism of excitation, mentioned in the last sentence of the extract quoted. In introducing my subject I borrowed imagery from the horticultural sector, but that is now so far behind us that in order to explain to you the mechanism of electroluminescence I shall transplant the action of this play of electrons to a sports field. The emission of light takes place during a jumping contest between electrons. Successful jumps are celebrated by the ignition of light signals, and these nimble quanta are presented with colours denoting the height cleared. The highest jumps are rewarded with violet or blue, the lower ones successively with green, yellow and red, while awkward little hops close to the ground are dismissed with infra-red. To enjoy visible light of a certain colour, then, we have to compel the electrons to make correspondingly high jumps. The stick used for measuring the height cleared by the electrons is graduated in volts, and we recall that to produce visible light we must make the hurdles between two and three volts high. For our chemists this is not a particularly difficult chore: all they have to do is to dissolve a spot of manganese in the zinc sulphide, which has the effect of producing hurdles of the right height all over the zinc-sulphide field. It is now up to the physicist to persuade the electrons to jump well. This he does, following the Frenchman Destriau, by applying an electric potential, thus setting the whole sports field on a tilt. Now the excitement really starts. The electrons break into a trot, and a few of them, those that don't stumble too much over the bumps in the ground, get up such a speed that they are able to clear the jump and we are rejoiced with a useful light quantum. Most of the little scamps, however, were born lazy and are content to jog-trot calmly down the slope, dodging craftily between the hurdles and hopping over mole hills, supplying us only with very long-wave infra-red quanta (i.e. heat radiation). The experimenter, determined to teach the recalcitrants manners, now makes the slope steeper and steeper, but this makes them so wild that very soon they completely destroy the sports field. "The panel has broken down again," sighs the physicist. As a trainer of jumpers, then, the physicist is ultimately not a great success, and he tells the lighting engineer that, as far as luminous panels based on the Destriau effect are concerned, he will have to be content with a low efficiency.

For a more effective electron trainer we again call in the help of the chemist, hoping that one of the numerous varieties in his bulky book of recipes will provide us with a better sports field. Recollecting a luminous effect discovered by the Russian Lossev whilst playing with an old-fashioned crystal detector in the days of Rapallo, we agree to have another try, this time with a proper semiconductor instead of the "quarter-conductor" zinc sulphide. Since the semiconducting carborundum of the crystal detector is not so very easy for our chemists to handle, we take the rather less wayward gallium phosphide, whose electro-optical properties resemble in many respects those of carborundum. In a pure state gallium phosphide forms a sports field the entire surface of which is completely occupied by electrons; above their heads there extends a system of scaffolding at just so many volts above the ground that electrons jumping down are able to produce light quanta of the required colour. In pure gallium phosphide, however, this superstructure is empty. The chemist therefore sets off to build on one half of the field, let us say the east half, a large number of donor pillars. Seated on these pillars are electrons that can easily step over to the scaffolding where, egged on by the notorious agitator Brown, they can take a walk around. For the present they dare not jump down to the fully occupied ground beneath them, for the great trainer Pauli has flatly forbidden them to perch on the heads of their own kind. Our chemist now prepares an opportunity for them to jump by removing individuals from the west half of the field (to be exact he lets them take a seat on fairly low acceptor bar-stools whose legs take up hardly any room on the grass). Vacant spaces are thus created where the jumpers can land without defying the dreaded Pauli. At this point the front ranks of the scaffold-walkers on the east side show an inclination to take the plunge towards the inviting vacant spaces in the west half. Simultaneously the eastern ground electrons start to make for them too, leaving similar gaps in their own ranks near the half-way line. (Although orthodox spectators might find all this difficult to follow, we broad-minded physicists regard it as perfectly normal and understandable that the eastern linesmen should consider these gaps in their own ranks as individuals, as aliens with subversive tendencies.) Those leaving their own territory, however, are punished by Coulomb with such a nostalgia that the crossing incidents very soon come to an end: Coulomb lets the aliens on both sides feel his powers by raising the whole of the west half to a level at which the occupiers of the bar stools are at the same height as the squatters on the pillars. In this deadlock the chemist sees no glimmer of light, and the physicist has to assume the initiative. Taking a simple battery of a few volts, he connects the positive pole to the west half and the negative pole to the east half, thereby crushing Coulomb's opposition and restoring the original difference in level between the eastern scaffold-walkers and the ground in the west half. Electrons now come forward in a steady stream to risk the jump, and every jump (in this ideal case) is successful. The electrical connections between the negative and positive poles of the battery are responsible for the supply and removal of the jumpers.

The ideal, which is to convert electrical energy into light with a high efficiency, has not yet in fact been realized. Working in close cooperation, physicists and chemists have been able in recent years to raise the efficiency of the Lossev effect to roughly the same level as that of the Destriau effect. Unlike the situation with the zinc-sulphide panel, however, the excitation mechanism in the case of the gallium-phosphide diode sets no fundamental limit to the efficiency of the conversion. The main difficulty in improving the efficiency is now to improve our control of the material. The gallium-phosphide crystals hitherto available, for example, are still very inferior in their physical and chemical purity to the transistor materials, germanium and silicon. There are many arguments that might be put forward to excuse this state of affairs; I shall mention here only two. A crystal consisting of a compound of two elements like gallium and phosphorus has more degrees of freedom by which it can escape our control than a single-element transistor crystal. Further, the amount of labour devoted to the perfecting of transistor materials may certainly be estimated as at least a hundred times greater than that devoted to gallium phosphide. The fact that the Lossev effect opens up interesting perspectives in many fields of application is now increasingly recognized. The moment it is possible to raise by a factor of ten the efficiency with which visible rays can be generated with this diode "lamp", it can become the "light-source of today". It might then in principle also be possible to replace the voluminous picture tubes in television sets by a "picture on the wall".

To make predictions is difficult, even for a physicist, whose profession prides itself on being able to describe with exactitude the future course of many phenomena from a given initial situation. Whether we shall ever in fact obtain from the Lossev diode an efficiency of 100 per cent or even higher — which, incidentally, would not be in conflict with physical laws, since a diode of this kind, biased in the forward direction, is able through the Peltier effect to draw heat from its surroundings and convert it into other forms of energy — whether we shall ever achieve that is a question you cannot expect me to answer today.

What is more to the point is that a Lossev source with an efficiency of only one per cent already makes very useful opto-electronic circuits possible. The very fact that the radiation is emitted less in the visible range than in the near infra-red is, as we have seen, an advantage in this connection. Moreover, the use of a DC supply of low voltage allows much better matching to the photoconductive part of the opto-electronic circuit and to other solid-state devices, such as transistors, diodes and magnetic cores, than is possible with the Destriau panel.

We trust that our chemists will press on bravely with their efforts to perfect their equipment for preparing pure gallium phosphide, equipment which, because of its combination of high pressure and high temperature, resembles in many respects a phosphor bomb. We physicists will meanwhile try to track down the evil-doers, the killers, who still stifle 99 per cent of the potential quanta at birth.

This brings me to the end of the survey I wanted to give you of my own working territory. The poet Hölderlin expressed in the following lines, freely translated, just how difficult it is for the uninitiated to grasp the essence of a subject unfamiliar to him: "He who merely smells my plant knows it not — nor yet he who plucks it merely to learn of it". To what extent have I succeeded as a guide on this tour in leading the uninitiated among you really *into* my garden, as I intended, and not "up the garden path"? I gladly leave the answer to this question to my fellow members of the guild, who may check the adequacy of the imagery which I have used against the imagery of our professional symbols and formulae.

Summary. Principal contents of the address delivered by the author upon his inauguration as professor extraordinary at the Technische Hogeschool, Eindhoven. Opto-electronics is concerned with the interaction of light and electrons in solids, and in particular with "r.e. effects", where optical radiant energy causes a change in electrical properties, and with the alternative "e.r. effects". After discussing photoconductivity, an r.e. effect, the author describes the potential applications and properties — such as power gain and response lag — of (e.r.-r.e.) combinations, and finally deals at greater length with electroluminescence, the most important practical representative of the e.r. effects. The mechanisms of the two known forms, i.e. the Destriau effect and the Lossev effect, are explained with a somewhat parodied version of the band scheme, and it is made clear why a high luminous efficiency is possible in principle with the Lossev effect but not with the Destriau effect.

PREPARATION OF GRANULAR PLASTIC FOR GRAMOPHONE RECORDS

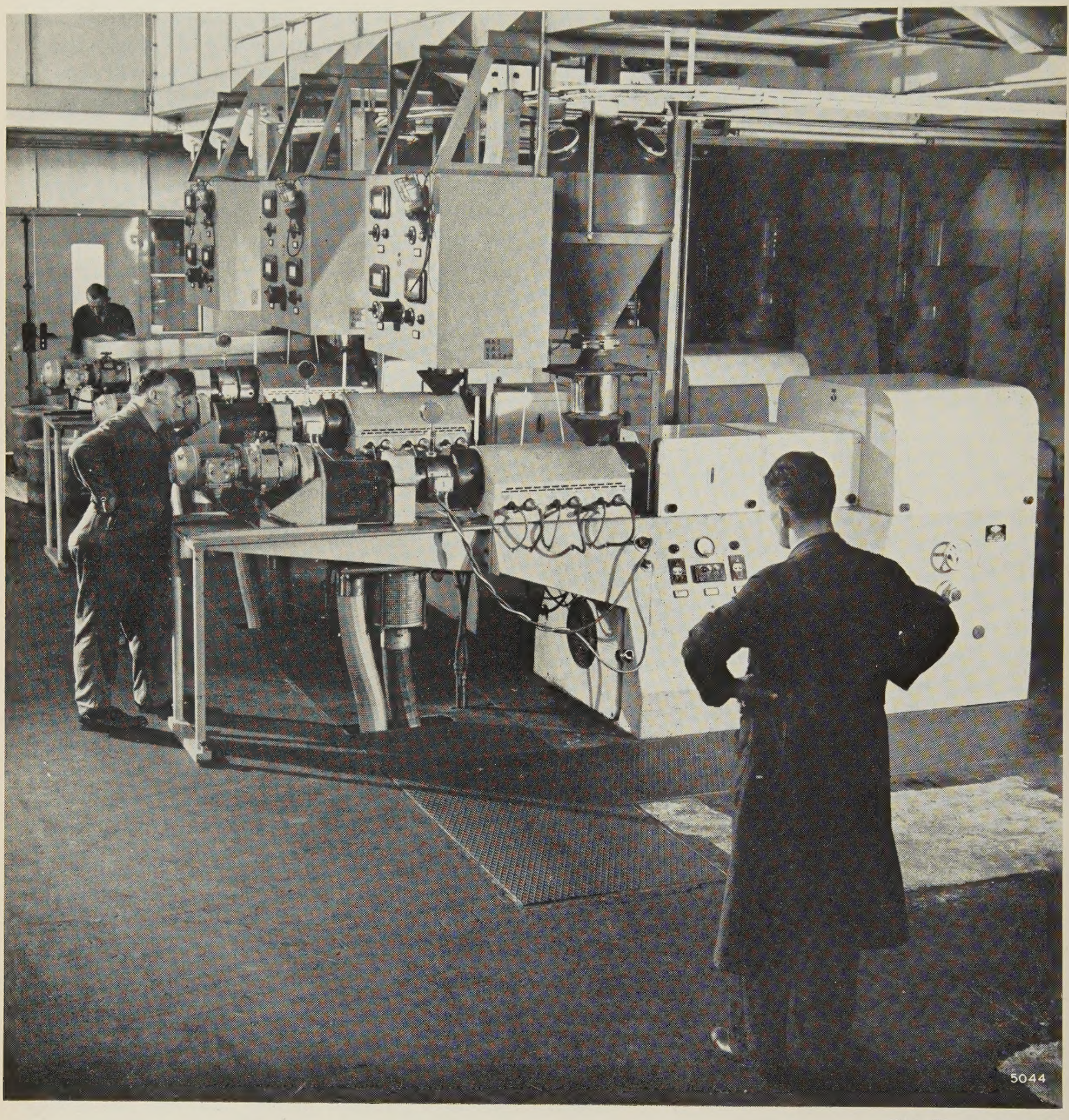

Photo Maurice Broomfield

The photograph shows part of the plant at Philips' Phonographische Industrie, Baarn, Netherlands, that converts a mixture of plastics in powder form to the granular material from which microgroove gramophone records are made. A powder mixture, prepared on the platform just visible at the top of the picture, descends through a hopper past a permanent magnet, which removes any iron particles. The mixture then enters an electric heating chamber. This is divided into three zones of different temperatures, which are kept constant by automatic controllers (in the console near the hopper). Two conveyor screws conduct the powder through the three zones. Thereafter it is compressed and compounded, i.e. kneaded into a homogeneous mass. The mass then passes to an extruding head and is extruded through a perforated plate in the form of strands about 5 mm in diameter.

At the left-hand end of the machine is the granulator. Here the still warm strands are reduced to grains by rotating cutters. The grains drop into a fast, filtered air stream, which cools them and conveys them to collecting bins. From this granular material the microgroove records are pressed ¹).

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¹) Philips tech. Rev. **17**, 108, 1955/56.

A 4 MeV INDUSTRIAL RADIOGRAPHY INSTALLATION

by T. R. CHIPPENDALE *).

621.386.8:621.384.62:620.179.152

For radiography of very great thicknesses of steel a harder radiation is required than can be delivered by conventional X-ray tubes. For generating a radiation of the required hardness, the electrons bombarding the target must have an energy of several MeV. An attractive method of producing electrons of such energy is by means of a linear accelerator. This makes for a manageable installation and an intense X-ray output which permits of rather short exposure times. With the installation here described, the exposure time for the radiography of a 12″ (30 cm) steel wall with 1 m focus-film distance, and using a slow, sensitive film, is less than half an hour; flaws about 0·75 mm across in the wall can then be detected.

Industrial radiography calls for a wide range of equipment capable of detecting flaws or irregularities in a considerable range of materials and specimen thicknesses. Conventional X-ray equipment operating at up to 300 or 400 kV has been commonly available for some time and has been found satisfactory in many engineering applications. However, the radiations produced at such voltages are too strongly absorbed for a useful penetration of heavier sections of materials, e.g. 7 cm or more of steel. For such a purpose, radiation of a much higher quantum energy than can be obtained with electrons accelerated to 400 keV is needed. Equipment has been designed successfully in which resonant transformers (up to 1 and even 2 MV) and Van de Graaff generators supply the voltage. More recently, radioactive isotopes have been used as radiation sources. The quantum energy of their γ radiation generally lies somewhere between 1 and 2 MeV, but with radioactive sources there is the disadvantage that the ratio between the size of the source and its intensity is unfavourable. To provide optimum radiographic definition an approximation to a point source is required; this cannot be achieved with a radioactive source of the required intensity.

For the radiography of steel above 7 cm in thickness X-rays generated by means of electrons of about 4 MeV are particularly suitable [1]). Great difficulties would be encountered in an attempt to obtain this energy of 4 MeV by making the electrons traverse a potential difference of 4 MV between cathode and target. There are, however, many kinds of particle accelerators, such as cyclotrons, betatrons, linear accelerators, etc., in which it is possible, without the application of very high voltages, to accelerate the particles to high energies. X-ray installations with betatrons supplying electrons with energies of 15 and 31 MeV have indeed been used [2]). Linear accelerators, however, also have very attractive properties for this purpose [1]). With a linear accelerator an intensely radiating X-ray focus of small dimensions can be obtained, which makes for short exposure times and high-definition radiographs.

In a linear accelerator, the acceleration results from the electrons "surf-riding" an electromagnetic wave travelling in a straight accelerator tube of special construction, known as a corrugated guide. The wave is generated by a magnetron that is coupled to the corrugated guide by a system of waveguides. To reach an energy of 4 MeV a corrugated guide with a length of 1 m is sufficient. As a linear accelerator is fairly light (magnets with heavy iron cores are not required) it can be used in the construction of an easily manoeuvrable installation in which the X-ray beam can be brought quickly into the desired position with respect to the specimen. In view of the fact that the specimens are generally heavy and difficult to handle, this is very important, particularly when it is a question of routine inspections. A rapid setting up makes it possible, furthermore, to take full advantage of the short exposure times required, especially for materials which are not too thick.

An X-ray installation for the inspection of heavy metal sections has been designed and constructed at Mullard Research Laboratories on behalf of Mullard Equipment Ltd, and delivered to the British Armament Research and Develop-

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*) Mullard Research Laboratories, Salfords, England.

[1]) C. W. Miller, Industrial radiography and the linear accelerator, J. Brit. Instn. Radio Engrs. **14**, 361-375, 1954.

[2]) Bau und Anwendungsmöglichkeiten von Betatron-Geräten, Stahl und Eisen **73**, 705-721, 1953; W. Lückerath, K. Fink and R. Flossmann, Durchstrahlen von heissen Vorblöcken aus Stahl mit einem Betatron und Sichtbarmachen des Durchstrahlungsbildes mit einem Röntgenbildverstärker und einer Fernseheinrichtung, Stahl und Eisen **79**, 1637-1646, 1959; W. J. Oosterkamp, J. Proper and M. C. Teves, X-ray inspection of hot steel billets during rolling, Philips tech. Rev. **21**, 281-285, 1959/60.

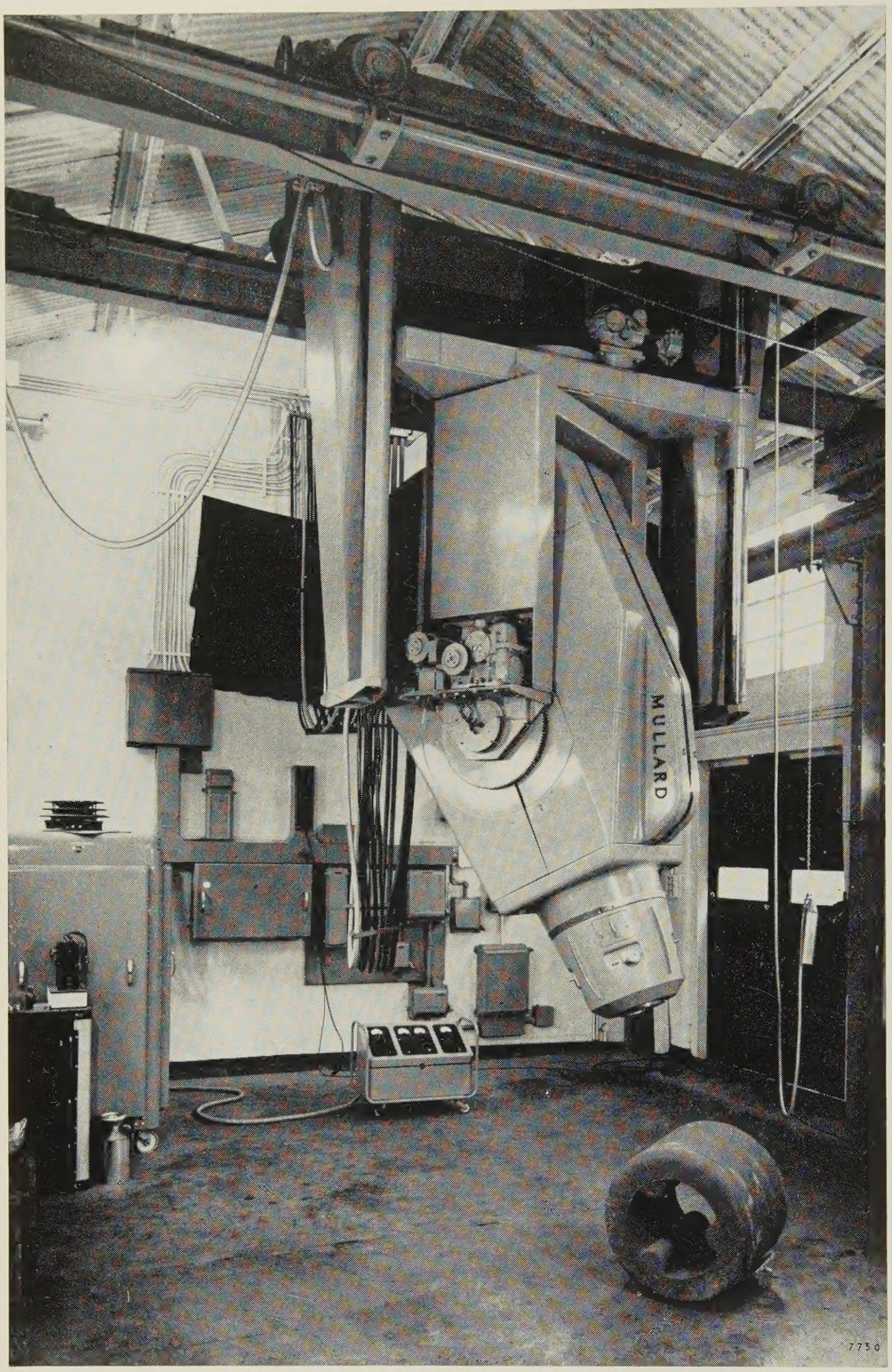

Fig. 1. General view of the 4 MeV X-ray installation constructed by Mullard Research Laboratories for the British Armament Research and Development Establishment. Apart from the accelerator and its suspension one can also see the modulator (in the cabinet with castors against the rear wall of the room) and the trolley with meters and controls of the three vacuum gauges, viz. Pirani, ionisation and Penning manometers. These components are discussed in the text.

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ment Establishment. This installation incorporates a 4 MeV linear accelerator. The experience obtained previously by the firm's laboratory in the manufacture of linear accelerators 3), in particular of various clinical X-ray installations that were also equipped with 4 MeV linear accelerators, proved of great value 4). This equipment which, as far as the author knows, was the first to be designed specifically for industrial radiography, was installed in June 1956 (*fig. 1*). Since then it has been used regularly and has proved its value. *Fig. 2* shows the exposure times required with this installation for various thicknesses of steel.

The corrugated guide with its magnetron and associated waveguide system and an adjustable X-ray beam collimator (X-ray head) are incorporated in a single unit — the accelerator assembly. This

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3) C. F. Bareford and M. G. Kelliher, The 15 million electron-volt linear electron accelerator for Harwell, Philips tech. Rev. **15**, 1-26, 1953/54.

4) An illustration with a short description of a clinical X-ray installation equipped with a 4 MeV linear accelerator was published in Philips tech. Rev. **17**, 31, 1955/56; a more complete description will be found in T. R. Chippendale and M. G. Kelliher, A linear accelerator for X-ray therapy, Discovery **15**, 397-404, 1954.

accelerator assembly is mounted in a suspension system that makes possible the requisite rapid and accurate setting up with respect to the specimen. Other main components are the modulator that supplies the accelerator assembly with 50 kV pulses, a trolley containing the meters required for the vacuum system (all shown in fig. 1), and the control desk and the power supply units (*fig. 3*) which are placed in a separate room protected against radiation. In *fig. 4* the relationship between the main components of the equipment is shown schematically.

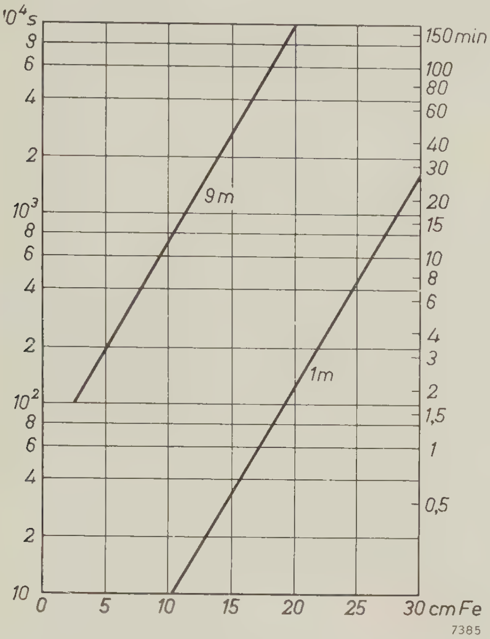

Fig. 2. Exposure time (in seconds and minutes) as a function of the thickness (in cm) of steel for the installation depicted in fig. 1 at target-film distances of 1 m and 9 m. Film used: "Ilford" Industrial F. Density: 2.5. Development 8 min at 20 °C in PQX 1. Lead screens: 0.1 mm front and 0.25 mm back. "Ilford" Industrial F is a slow, high-resolution film; for the faster "Ilford" Industrial C film the exposures should be multiplied by 0.7.

The present paper deals with the suspension of the accelerator assembly, the adjustable X-ray head, the vacuum system, the focussing of the electron beam on the target and the X-ray output, and it presents some information on attainable results. Next some features of the electron accelerator equipment are discussed, viz. particulars about the modulator, the electron gun, the rectangular waveguide system, and the corrugated guide. At the end of the article there is brief mention of a more recent installation, equipped with a similar accelerator, which is fully transportable.

Suspension

The suspension (*fig. 5*) of the accelerator assembly is reminiscent of a travelling crane. On its front the accelerator housing carries the adjustable X-ray head, from which the X-ray beam emerges. The accelerator has five independent electrically motorised movements.

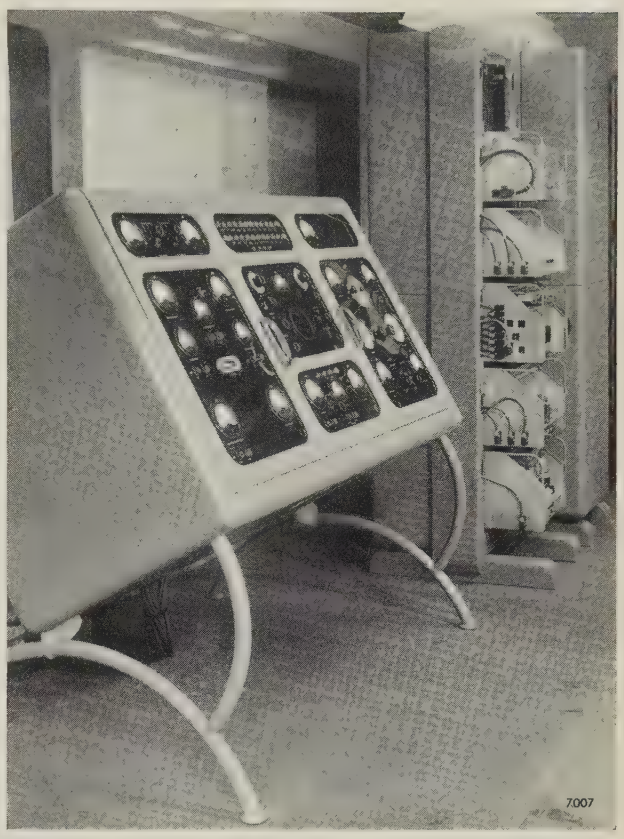

Fig. 3. Control desk. In background, two cabinets housing the power supplies, one opened. The room housing these units of the X-ray installation is shielded against radiation.

First of all the accelerator assembly is slung from two horizontal stub axles in a U-frame *3* and can thus tilt from 5° above the horizontal to 5° beyond the downward vertical. To minimise the mechanical requirements of the motor and transmission, accommodated in the U-frame (see fig. 1), the accelerator assembly with its X-ray head and all connecting cables and hoses are balanced about the stub axles. The stub axle *1* visible in fig. 5 contains the vacuum line that connects the corrugated guide to the oil-diffusion pump. A special rotatable vacuum-tight coupling in

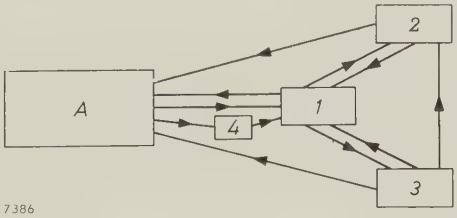

Fig. 4. Schematic diagram of the installation. *A* accelerator. *1* control desk. *2* modulator. *3* power supplies. *4* vacuum gauge trolley.

this line (to be discussed presently) permits the pump to remain vertical when the accelerator assembly is tilted.

Secondly the U-frame is suspended from the lift tray *7* by a short hollow shaft 30 cm in diameter. Thus the accelerator assembly can rotate through 45° to either side of the central position.

Thirdly the lift tray can be moved up and down over a distance of 2.5 m by means of fixed nuts, on two diagonally opposed corners, which pass over vertical lead-screws *2*. These $1\frac{1}{2}''$ lead-screws are mounted on the drop members *4* of the suspension frame forming the traversing trolley. The whole is constructed of 6 mm steel sheet in internally webbed box formation. The lead-screws are driven via a worm gear by a motor mounted on the traversing trolley. Two hollow 10 cm guide shafts *5*, and 45 cm long bushes *6*, on the other diagonal of the traversing trolley ensure smooth movement.

Fourthly the traversing trolley runs on rails that are mounted on I-section girders; these connect the gantry trolleys.

Fifthly the gantry travels the length of the room on rails mounted on stanchions. In the installation here discussed the distances over which gantry and traversing trolley can ride are limited by the construction of the building to about 2.5 m. All movements are provided with limit switches and mechanical safety stops.

The contactors for the motors operate for safety at 24 volts. The gantry control switches are carried in a small unit suspended from the traversing trolley. To bring the accelerator assembly into the desired position, only one hand is required. The weight of the gantry and all the components it supports is about $3\frac{1}{2}$ tons (3400 kg). Of this weight the X-ray head accounts for about 360 kg, while the accelerator housing and its contents contribute about 720 kg.

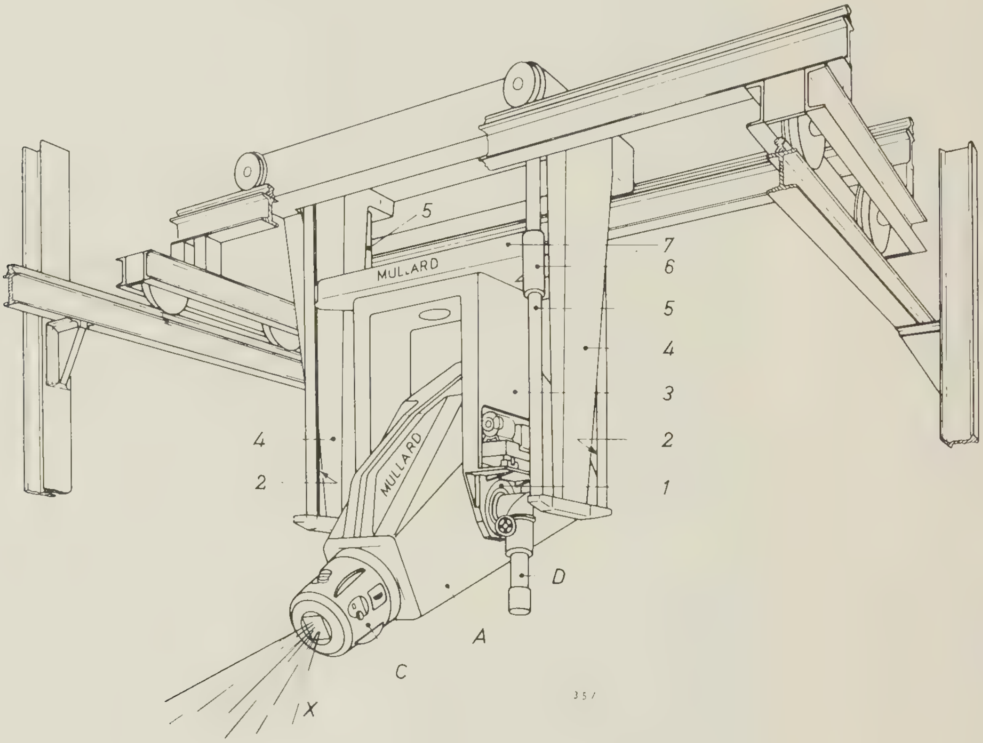

Fig. 5. Diagram of the suspension of the accelerator assembly. *X* X-ray beam. *C* X-ray head providing an adjustable rectangular radiation field. *A* accelerator. *D* oil-diffusion pump. *1* one of the stub axles about which the accelerator assembly can be tilted. *2* vertical lead-screws. *3* U-frame. *4* vertical drop members. *5* guide shafts. *6* guide bush. *7* lift tray. Speeds of the five motorised movements: tilt and swivel, both 2°/sec; vertical displacement, about 1.2 m/min; both horizontal displacements, about 1.8 m/min. The X-ray head can be rotated manually about the beam axis through 360° (see fig. 7).

X-ray head

When fast electrons are intercepted by a target, X-rays are produced which tend increasingly to concentrate in the forward direction the higher the energy of the electrons. For this reason X-ray installations for very hard radiation have a transmission target (*fig. 6*) instead of a target such as is used in conventional X-ray tubes. The transmission target must be of such a thickness that the X-ray output is at its maximum, i.e. it must be thick enough to intercept all electrons but not so thick that the output is reduced unduly as a result of absorption of the X-rays. There remains, however, considerable radiation both laterally and towards the rear. An X-ray head has therefore been developed that ensures that the radiation intensity in all directions but that of the useful beam is attenuated to an arbitrary level of less than 0.1% of that along the axis of the beam.

Fig. 7 shows the construction of the X-ray head, which is basically similar to that used in the above-mentioned clinical version from which it was developed. The transmission target is fixed at the end of the target snout, an extension of the vacuum envelope of the corrugated guide that projects some way into a lead block *4*, fixed rigidly to the accelerator. Close to the target there is an additional cylinder *3* of "heavy alloy", a strongly absorbing tungsten-copper alloy (density = 17 g/cm³). The blocks *3* and *4* contain a conical hollow for the X-ray beam. The cone defined by the hollow of the blocks has, at a distance of 1 m from the target, a diameter of 26 cm, and halfway through the target, which has a thickness of 3 mm, a diameter of 2 mm. (The focus of the electron beam *on* the target has a diameter of less than 2 mm.) There are, however, still a fair number of stray electrons in the corrugated guide that impinge on the target outside the X-ray focus. It is in order to absorb the X-ray radiation produced by these stray electrons, and thus to maintain the quality of the focus, that the tungsten-copper block *3* is used.

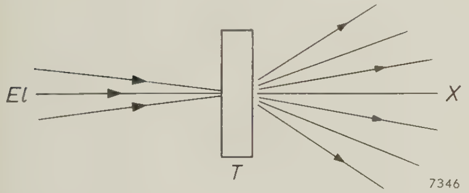

Fig. 6. Transmission target. If use is made of the X-ray radiation *X* emitted by a target *T* in the direction of the incident electron beam *El*, it is customary to speak of a transmission target. If the energy of the electrons is very high, e.g. 4 MeV, most of the X-rays are emitted in this direction.

At the lower end of the fixed collimator are mounted three ionisation chambers, one after the other. One of these provides a measure of the dose

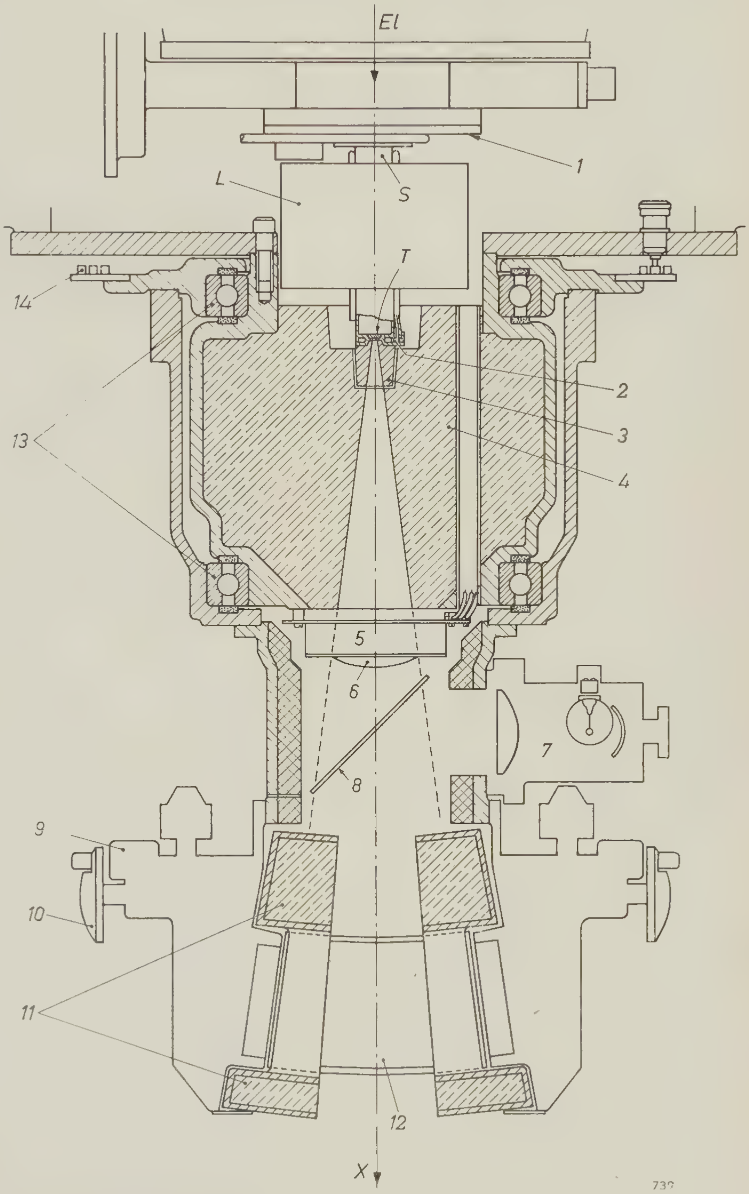

Fig. 7. Diagram of the X-ray head. *El* electrons from the accelerator. *1* end face of vacuum envelope. *S* target snout carrying at its end a 3 mm tungsten target *T*, set in the water-cooled copper block *2*. *L* magnetic quadrupole lenses focussing the electrons upon the target (cf. fig. 12). *3* block of heavy tungsten-copper alloy. *4* lead collimating block. *5* three ionization chambers for the measurement and the control of the radiation. *6* flattening filter (rarely used). *7* optical system used with mirror *8* to provide a parallel light beam for the positioning of the accelerator with respect to the object. *9* digital counters indicating the dimensions of the irradiated field at 1 m from the target *T*. *10* handwheels for the adjustment of the lead screens (jaws) *11* and *12*, that provide an adjustable rectangular diaphragm. *X* X-ray beam. *13* ball races enabling the rectangular diaphragm to be rotated. *14* slip-rings for electrical connections.

rate, a second gives the integral dose, while the third is part of a device to be described later for the automatic centring of the electron beam. Just below the ionisation chambers there is space for a correction filter for flattening the X-ray field distribution. It was found, however, that such a beam-flattening filter (frequently used in medical applications) is hardly ever necessary in industrial radiography. The reason will be discussed presently.

The X-ray cone defined by blocks *3* and *4* (fig. 7) is further limited to a beam of rectangular section by two pairs of lead screens. Each of these screens is 10 cm thick in all; in one of the pairs this total is achieved in two stages for constructional reasons. By means of handwheels each pair may be opened or closed like the jaws of a pair of pliers about an axis through the focus. In this way the inner face of the diaphragm always coincides with the outer edge of the required X-ray beam, thus minimising scatter. By the side of each handwheel there is a digital indication of the dimensions (in mm) of the associated field at a distance of 1 m from the focus (cf. fig. 8). This field is adjustable between the limits of 3 × 3 cm and 15 × 25 cm. Because of experience since obtained, the maximum field in the new version of the installation has been increased to 25 × 30 cm.

The lower part of the X-ray head, and thus the rectangular beam collimators, can be rotated about the beam axis.

To permit of ready positioning of the accelerator a source of light is incorporated which, via a lens and mirror system, projects a parallel beam of light along the axis of the X-ray beam. Alternatively the system could be so arranged that the light source appears to be situated at the focus. The light beam would then illuminate exactly the field covered by the X-ray beam. At normal levels of room illumination this system only works well at small focus-specimen distances unless use can be made of reflective devices (e.g. adhesive tape with lenticular reflecting surfaces) that can be affixed to the specimen.

Vacuum system

The vacuum in the corrugated guide (pressure about 3×10^{-6} mm Hg) is maintained by continuous pumping with a 10 cm oil-diffusion pump (*fig. 8*), which is combined with a baffle valve. The pumping speed above the baffle valve is 150 l/sec. A rotary backing pump is mounted on the U-frame of the suspension. A fork (*10* in *fig. 9*) fixed to the U-frame holds a pin projecting from the baffle valve and so keeps the diffusion pump vertical as the accelerator assembly is tilted. To make tilting possible, the

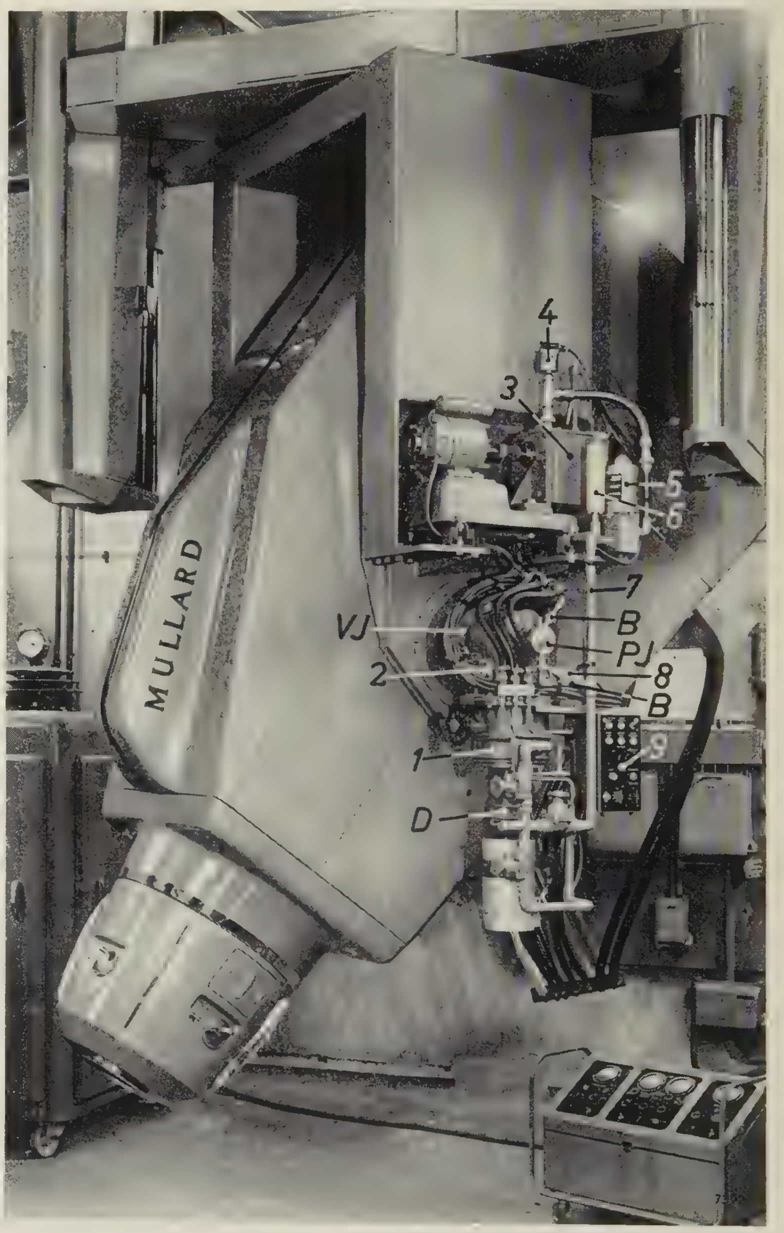

Fig. 8. Arrangement of the vacuum pumps. *D* oil-diffusion pump. *1* baffle valve. *2* ionisation gauge for the high vacuum. *VJ* rotatable vacuum-tight joint (cf. fig. 10) enabling the pump *D* to remain vertical when the accelerator is tilted. *3* backing pump. *4* and *5* magnetic safety valves. *6* Pirani manometer for the backing vacuum. *7* rigid connection between *D* and *3*. *B* backing line to electron gun (discussed on p. 203). *PJ* rotatable joint in *B* (cf. fig. 10). *8* Penning manometer operating a vacuum safety interlock device. *9* control panel.

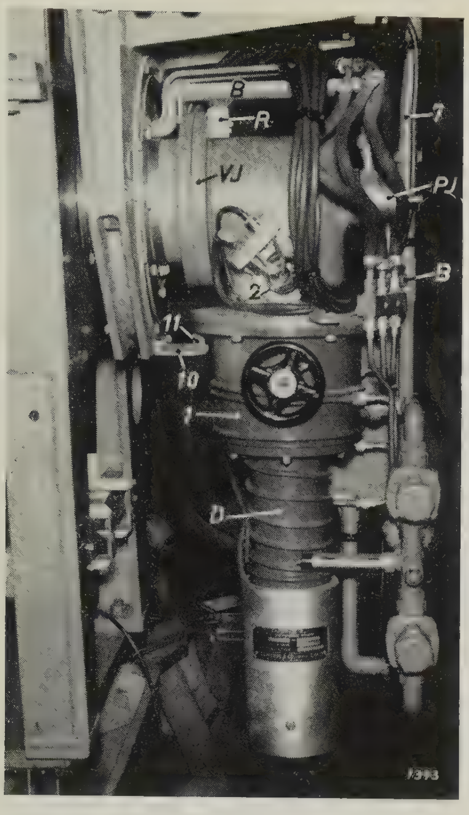

Fig. 9. Detail of the vacuum pump installation showing the fork *10* and the pin *11* that hold the pump *D* in a vertical position when the accelerator assembly is tilted. *R* is a reservoir with vacuum oil for the rotatable joint *VJ* (cf. fig. 10). The other characters have the same significance as in fig. 8.

15 cm vacuum line incorporates a rotating joint. Its construction is explained in *fig. 10*. Joints of this type have been operated successfully in lines of up to 20 cm diameter for clinical accelerators. As there is no relative movement between backing pump and diffusion pump, the line connecting them is rigid. A small rotating joint is however mounted in a branch *B* of the backing line leading to the electron gun of the accelerator. This branch is used if the cathode of the gun has to be replaced, as will be discussed presently. The construction of this small joint is also shown in fig. 10. The control panel for the vacuum pumps is mounted alongside the diffusion pump. Magnetic valves protect the diffusion pump against mains failure. The backing pressure is measured by means of a Pirani gauge, while the high vacuum is measured by means of a triode ionisation gauge. A Penning gauge is incorporated for the operation of a relay circuit that actuates a safety system if the pressure becomes too high. The controls and meters of these three vacuum gauges are accommodated on a trolley (fig. 1) that is connected to the gauges by means of a long flexible cable. The whole arrangement is rather similar to that of the 15 MeV linear accelerator described previously in this journal [3]).

Beam focussing and target

Fig. 11 shows the electron distribution in the practically parallel beam supplied by the accelerator. It will be seen that over 90% of the electrons fall on the target within a circle of 1 cm diameter. For many applications of the accelerator such a relatively large beam size is not a disadvantage, for example if the accelerator is part of a neutron generator, or if the

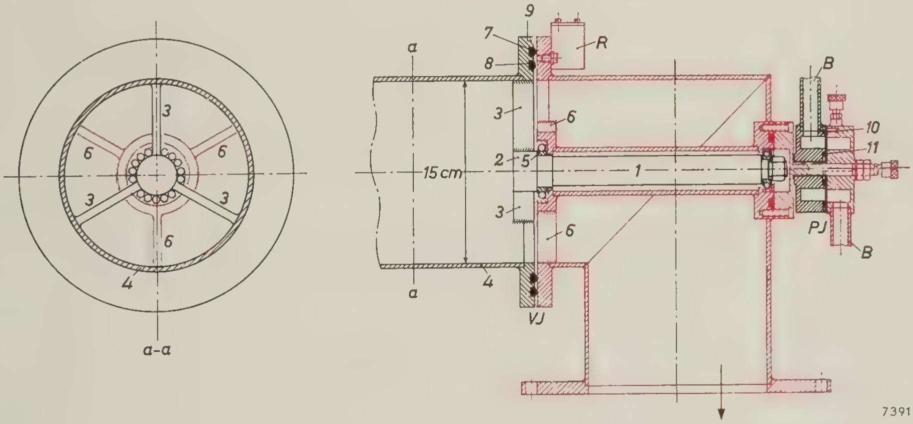

Fig. 10. Construction of the rotatable joints *VJ* and *PJ* (figs 8 and 9) in the 15-cm high-vacuum line and in the backing line *B* to the electron gun. The parts printed in black turn with the accelerator when the latter is tilted. The elbow-piece, printed in red, under which the oil-diffusion pump is fixed, remains stationary. The red part on the right is fixed to the elbow-piece. The thicker part *2* of the stub axle *1* is held, by means of spokes *3*, in the high-vacuum line *4* to the accelerator. The ball race *5* fits in a mount held in the elbow piece by means of spokes *6*. The two concentric O-rings *7* and *8*, with vacuum-oil lubricant in between, form a vacuum-tight seal. The rings bear on the polished chromium-plated flange *9* of the elbow-piece. The force with which the rings are compressed is adjusted by means of distance pieces at the ball races. *R* is a reservoir containing vacuum oil.

In the case of the coupling *PJ* in the backing line *B*, sealing is performed by means of the O-rings *10* and *11*, smeared with vacuum grease.

electron beam itself is to be used for irradiation. A strong concentration of the beam is indeed unfavourable in the latter case, because this would only lead to a high local load on the output window and would make its construction unnecessarily difficult. For radiographic purposes, however, a smaller focal spot is required. In clinical linear accelerators a focal spot size of 5 mm is considered small enough for limiting the penumbra, i.e. to produce a sharp enough cut-off at the edge of the treatment area.

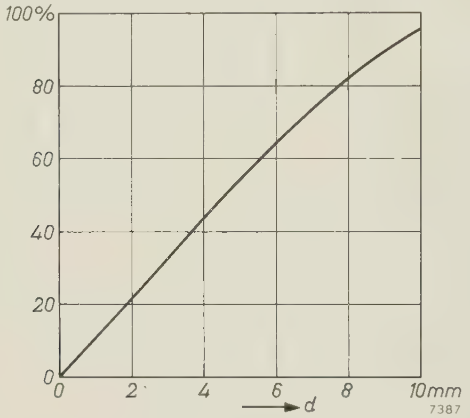

Fig. 11. Percentage of the electrons in the beam that fall on the target within a circle of diameter *d*.

For industrial radiography a focal spot not larger than 2 mm is desirable, viz. sufficiently small to reduce geometrical unsharpness in the radiographic image to the same order as that produced by other sources of unsharpness. A focus of 5 mm can be obtained by means of a system of stops in either the electron beam or in the X-ray beam. The argument has been that for clinical work the loss of about 40% of the output (see fig. 11) is of no consequence, as the remainder is so large that exposure times are still very short for the usual therapeutic doses. If, however, this method of collimation were to be extended to a focal spot of 2 mm diameter, fig. 11 shows that 80% of the output would immediately be wasted. For industrial radiography, where one is always fighting long exposure times, this is not acceptable.

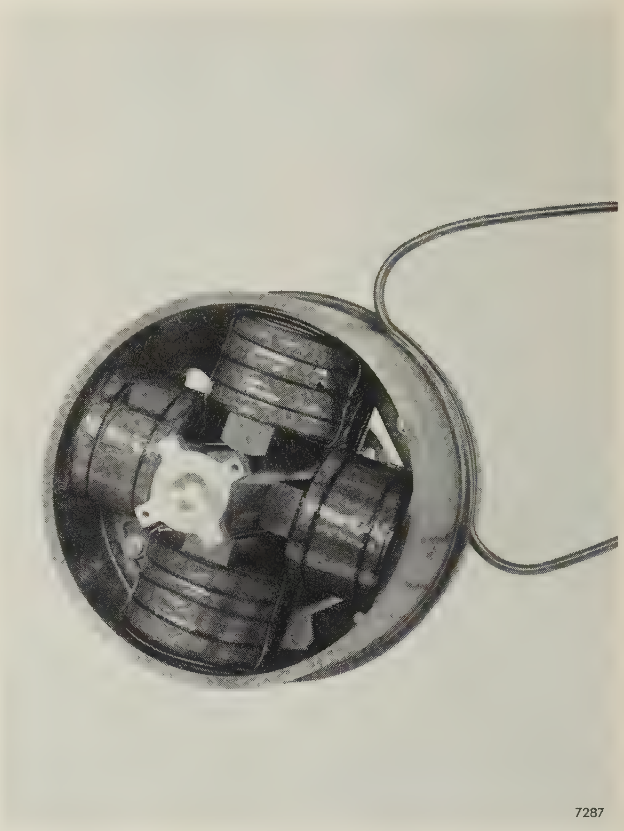

Fig. 12. Magnetic quadrupole lenses on the target snout of the accelerator. The illustration shows the four poles of the front lens. The second lens is immediately behind.

Magnetic lenses were therefore fitted on the target snout. As only little space was available, we have made use of a system of two magnetic quadrupole lenses (*fig. 12*). Such a system, first described in 1952 by Courant *et al.* ⁵), requires less space and power than a conventional axially symmetrical magnetic lens.

The performance of the lenses was investigated in a number of ways. An accurate measurement of the high-power high-energy electron distribution proved by no means easy. In the first place an extension of the method described by Bareford and Kelliher ³) was attempted. The measuring device shown in *fig. 13* was used. The measured 90% transmission

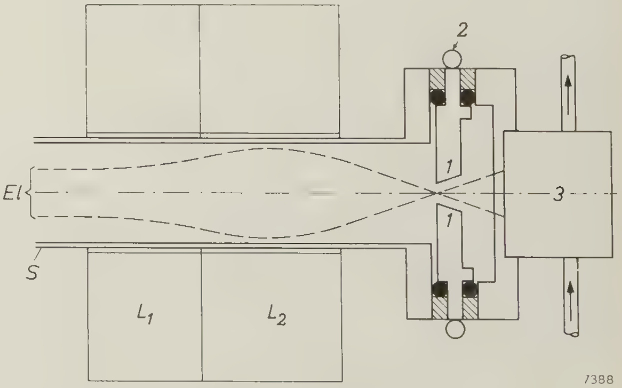

Fig. 13. Set-up for the calorimetric determination of the percentage of the electron beam *El* concentrated by the magnetic quadrupole lenses L_1 and L_2 inside a 2 mm diameter circle. The copper disc *1*, thermally insulated and mounted at the position of the target, is provided with a 2 mm hole. From the temperature rise of both the water in the cooling circuit *2* of disc *1* and that in the calorimeter *3*, the required percentage can be deduced. O-rings provide vacuum sealing.

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⁵) E. D. Courant, M. S. Livingston and H. S. Snyder, The strong focusing synchrotron. A new high energy accelerator, Phys. Rev. **88**, 1190-1196, 1952; see also: R. M. Sternheimer, Double focusing of charged particles by a system of two magnets with non-uniform fields, Rev. sci. Instr. **24**, 573-585, 1953.

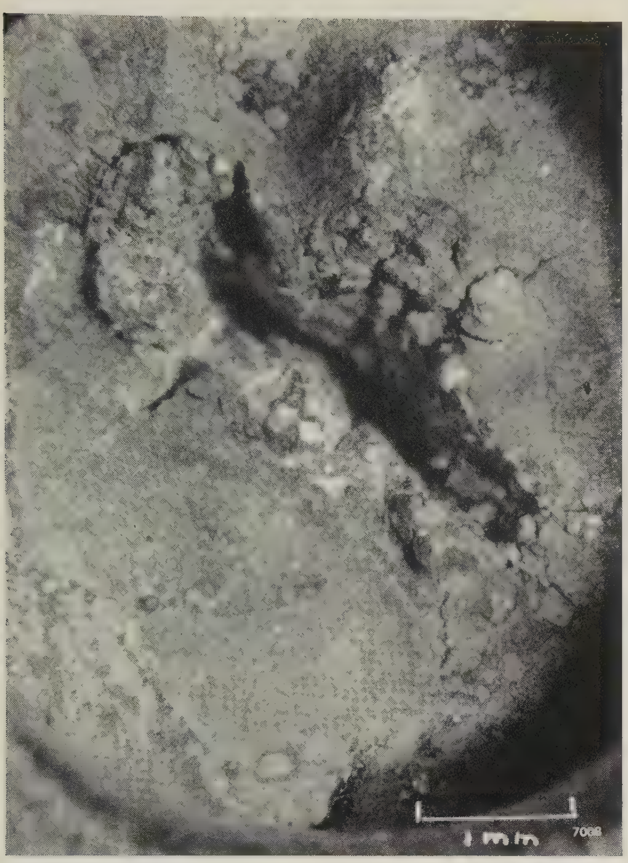

Fig. 14. Effect of the focussed electron beam on a gold target after exposure for about 1.5 hours.

through the 2 mm hole in the copper plate replacing the target is, however, probably erroneous owing to an unknown amount of reflected scatter from the innermost sections of the calorimeter assembly. We estimate that in fact about 95% came through.

In a second method a piece of photographic paper was placed at the focus. From this it was found that the focus was elliptical and certainly not greater than 2×1 mm. The most accurate estimate was, however, obtained from an examination of a gold target exposed for about 1·5 hours to the electron beam (*fig. 14*). From the shape of the hole at a depth of 2 mm, convincing proof was obtained that the dimensions of the focus were 1.5×0.5 mm. The larger dimensions on the surface are the result of an initially incorrect adjustment of the lenses.

In a quadrupole lens the north poles and south poles alternate, so that similar poles face each other diametrically. The optical equivalent of a quadrupole lens is a lens pair consisting of two mutually crossed cylindrical lenses of equal focal length, one positive and the other negative. The system consists of two such lens pairs L_1 and L_2, with focal lengths $\pm f_1$ and $\pm f_2$. L_1 and L_2 are mutually rotated by 90°, so that *fig. 15* represents the optical equivalent of the complete system. Rays of light such as l', parallel to the axis and in the vertical plane of symmetry, are therefore subjected first to a converging and then to a diverging effect. In the case of the rays like l'' in the plane of horizontal symmetry it is just the other way round. Rays l' and l'' at the same time represent the projections of the ray l on the planes of symmetry. Thus the path of an arbitrary ray parallel to the axis is also readily conceived. By means of the elementary lens formula, applied for both planes of symmetry, it is a simple matter to deduce that the rays l' and l'' intersect the axis in the same point F, i.e. that the foci in the two planes of symmetry coincide, provided that

$$f_1^2 - f_1 f_2 = d^2,$$

where d is the distance between L_1 and L_2. Any arbitrary ray parallel to the axis will now also pass through F, so that the beam is focussed in this point.

The condition of coincident foci does not yet completely determine the magnitudes of f_1, f_2 and d. There is still a certain degree of freedom in the design, which in this case has been used for accommodating the lens system in the limited available space (in the X-ray head a cylindrical space of 15 cm diameter and 15 cm length was available).

To make the focus F lie exactly in the target, it is necessary to make the power of the lenses adjustable in such a way that the condition of coincident foci is maintained. This is achieved by fine trimming of the current in the two lenses by means of mechanically coupled variable resistors.

Even if the two foci coincide, the system of fig. 15 still produces distorted images because of the fact that the magnification in the vertical plane differs from that in the horizontal plane. If the incident beam is exactly parallel, this is not noticeable, but in our case the beam contains rays making angles of up to about 0.005 radians with the axis. As a result the focal spot takes on an elliptical form. A spread in the electron energy of ±0.25 MeV ("chromatic aberration") also contributes to this effect. From a theoretical estimate of the effect of the various factors on the sharpness of the focus it follows that the two above-mentioned factors are the most important, and that the focus can be expected to be not larger than 2×1 mm. As stated above, it has proved to be 1.5×0.5 mm from the experiment with the gold target.

It will be clear from fig. 14 that gold, preferred as a target material for ease of soldering and its high thermal conductivity, cannot withstand the heavy specific loading of over 1000 W/mm² (850 W on the

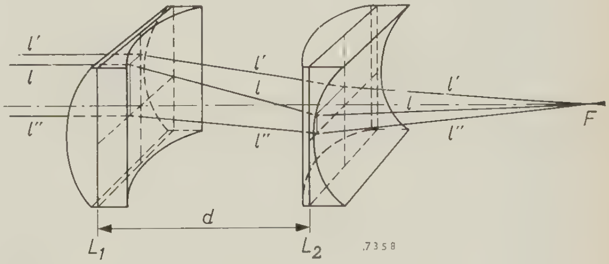

Fig. 15. Optical equivalent of the two magnetic quadrupole lenses. *Each* lens corresponds to a positive and a negative cylindrical lens (of identical focal lengths) in a mutually crossed configuration; the two lenses are also mutually crossed. A beam of light incident in a direction parallel to the axis is concentrated in a point F, provided that a certain relationship (see text) is maintained between the distance d and the focal lengths associated with L_1 and L_2.

1.5×0.5 mm focus). The target actually used therefore consists of a tungsten disc of 5 mm diameter and 3 mm thickness. This disc is mounted in a copper block in which an annular canal for cooling water is formed as close to the tungsten as is permitted by mechanical reliability. A 0.1 mm layer of the copper block is retained on the atmospheric side of the target to form a continuous vacuum enclosure, as large-diameter tungsten rod (from which the target is cut) can exhibit porosity along the length of the rod.

An average loading of 1000 W/mm^2 of the focus is several times the usual loading in conventional X-ray tubes. That the tungsten target can nevertheless withstand this load is due to the higher electron energy, giving a *volume* loading rather than a purely *surface* loading.

It is found that the position of the focus on the target depends to some extent on circumstances, e.g. the beam current and the high-frequency power. As it is necessary for the focus to be exactly behind the opening in the collimator block *3* (fig. 7), one of the three ionisation chambers *5* incorporated in the X-ray head is divided into four quadrants. Each quadrant supplies a separate current, and these currents (via amplifiers) control the currents energizing a pair of mutually crossed deflection coils that keep the electron-beam focus exactly aligned with the collimator aperture.

X-ray output

In any given linear accelerator the maximum X-ray output is governed by the maximum permissible duty cycle of the radio-frequency source. With the VX 4061 magnetron (2999.5 Mc/s) used, this maximum is fixed at a value of 0.001, corresponding to a pulse length of 2 μsec at a repetition frequency of 500 pulses per second. In practice, X-rays are only emitted for a part (1.8 μsec) of each RF pulse because of the filling time of the system. The repetition frequency can be selected at 100, 200, 300, 400 or 500 per second, which provides a directly proportional step-wise control of the X-ray output. Fine control, normally only used for tuning to maximum output at the selected repetition frequency, may be achieved by adjusting the electron-gun filament current.

It is common practice to characterise an X-ray installation by giving the *dose rate* in r/min (röntgens per minute) on the axis of the X-ray beam at a distance of 1 m from the target. This quantity is more readily measurable than the *intensity* (watt/cm^2). With only the heavy alloy block *3* (fig. 7) in position, and without the magnetic lens, the above-mentioned dose rate amounts to 750 r/min for the installation here described. With the lens operating, this figure is reduced to 600 r/min. This does not imply the loss of useful X-ray photons. When the lens is used, the electron beam is made to converge on the target, which results in a more divergent X-ray beam. This is an advantage as the available radiation is now distributed more uniformly over the irradiated field (*fig. 16*). It will in fact hardly ever be necessary to insert a special flattening filter (*6* in fig. 7) into the X-ray beam: it is found that with the cone angle chosen, the radial change in attenuation due to both the change in effective thickness traversed by the X-rays and the non-flat polar diagram still gives a tolerable range of film densities across the full field.

In fig. 15 it is seen that the rays show a different convergence towards the focus in the two mutually perpendicular planes of symmetry. Fig. 16 shows how this difference also manifests itself in the distribution of the dose rate over the irradiated field.

Performance

Fig. 17 gives an idea of the size of inclusions that can be detected in steel with the installation described in this article. These results are obtained using "Ilford" Industrial C film. On average they are very similar to the results obtained by Möller and Weeber using betatrons [6]). However, the X-ray output of the linear accelerator is so large that it is possible to take advantage of the high resolution of slow, ultra-fine grain films (e.g. "Ilford" Industrial F) without the necessity for uneconomically long exposure times. The resolution is thereby increased [7]). For example, the size of inclusions which can be detected in a 30-cm steel wall is about 0·9 mm with Industrial C and about 0·75 mm with Industrial F. Data on the exposure times for "Ilford" Industrial F have already been given in fig. 2. We see from this figure that e.g. the exposure time for 30 cm of steel with a focus-film distance of 1 m is less than half an hour. The times given are those when lead intensifying screens are used, 0.25 mm thick behind the radiographic film and

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[6]) H. Möller, W. Grimm and H. Weeber, Arch. Eisenhüttenw. **25**, 279-291, 1954 and **26**, 603-609, 1955. Möller and Weeber (Arch. Eisenhüttenw. **32**, 107-112, 1961, No. 2) also investigated a Mullard 4.3 MeV linear accelerator of the type described here (with an elliptical focus of 1.5×0.5 mm, not a circular one 5 mm in diameter as erroneously assumed by them). Their results were, however, based on radiographs which were not really representative of the best performance of this equipment. It is not surprising, therefore, that they found a poorer wire perceptibility than we did.

[7]) The improvement in resolution is about two wires and one wire respectively, in the case of the standardised penetrameter tests DIN Fe 2 and DIN Fe 3.

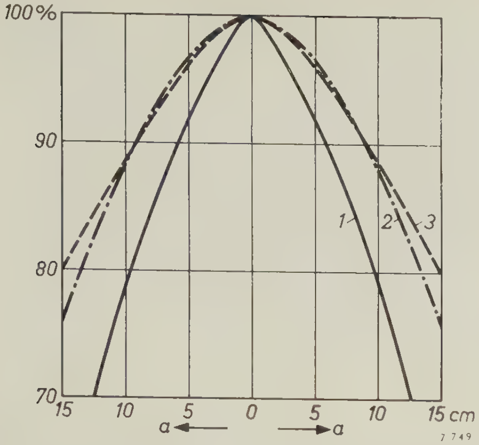

Fig. 16. Relative intensity of the X-radiation in a plane normal to the beam axis at 1 m from the target, as a function of off-axis distance *a*. These measurements were made with only the heavy alloy slug (*3* in fig. 7) in position (lead block absent). Curve *1*: without focussing by the magnetic quadrupole lenses. Curves *2* and *3*: with focussing, and measured in two directions at right angles in the two planes of symmetry of the quadrupole lenses. The difference between curves *2* and *3* reflects the unequal convergence of the electrons in the two planes of symmetry (cf. fig. 15).

0.1 mm thick in front of it. This combination gives a 2- or 3-fold intensification due to photo-electrons liberated by the X-rays in the lead foils. Intensifying screens consisting of fluorescing salts are not suitable for the very hard radiation delivered by the accelerator.

"Ilford" Industrial F film is also advantageous because no complications arise with regard to development. For some types of film, developing conditions may require adjustment in order to minimise the blotchy development characteristic of high-energy radiation. Moreover, development conditions vary the relative speeds of films. It was found, for instance, that exposure doses for any given density were in the ratio of 1.0 for "Ilford" Industrial C film, 1.75 for "Ilford" Industrial F and 6.0 for "Kodak" M when developed in ID 19 for five minutes at 20 °C, but when developed in PQX 1 for eight minutes at 20 °C the ratio was 1.0:1.5:3.9. If it is also borne in mind that a high-contrast developer such as PQX 1 tends to give better penetrameter sensitivity results, one can appreciate the dangers and difficulties of comparing performance measurements made by different workers.

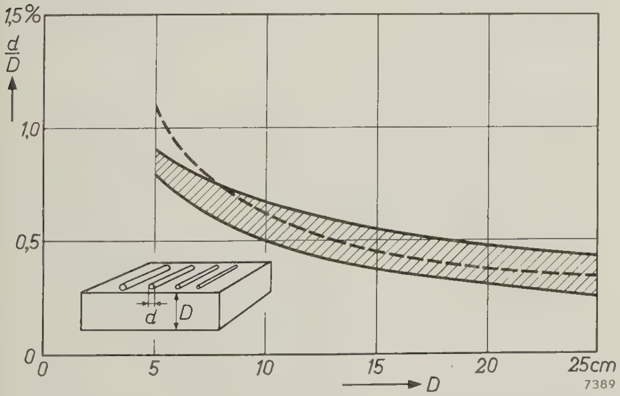

Fig. 17. Wire penetrameter sensitivity in steel for the 4.3 MeV linear accelerator, for "Ilford" Industrial C film (shaded area). This sensitivity, expressed as the percentage thickness (d/D) of the thinnest wire still just perceptible, is plotted as a function of the thickness D of the steel. The broken line refers to results obtained with a 31 MeV and a 15 MeV betatron installation by Möller and Weeber [6].

As the linear accelerator works with very short pulses (1.8 μsec), it is ideally suited to stroboscopic radiography (for example, of an internal-combustion engine [8]). Facilities are provided to allow the modulator to be triggered from an external source. One may, therefore, synchronise the pulse repetition frequency of the accelerator to some rotating or reciprocating device. A relative velocity between subject and film of 100 m/sec causes a blurring of approximately 0.1 mm on the film.

There follow now a few particulars concerning the linear accelerator proper.

The modulator

The modulator (see fig. 1) supplies 50-kV 2-μsec pulses to the magnetron and simultaneously to the electron gun of the accelerator. The modulator is basically similar to those used for magnetrons in radar transmitters [9]. As stated, the repetition frequency is stepwise adjustable from 100 to 500 per second. Because of the mobile suspension of the accelerator, the modulator is connected to it by a flexible coaxial cable of 2.5 cm diameter, insulated with polythene. In comparison with the modulator reported in 1953 in this Review [3], only two important modifications have been incorporated. Firstly, to permit of movement of the accelerator assembly, the 5 : 1 ratio output pulse transformer has been removed from the modulator cabinet and installed alongside the magnetron in the accelerator unit. The advantage of this is that the cable between the modulator and the accelerator requires to be insulated for a maximum voltage of only 10 kV instead of 50 kV. Furthermore it is better that the extra capacitance due to the long length of pulse cable is inserted on the input side of the pulse transformer rather than on the output side. The second modification has been to take advantage of the development of suitable high-power hydrogen thyratrons to replace the ignitron originally used as a switching valve. As already stated in the above-

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[8] Stroboscopic radiographs of a rotating internal-combustion engine, made with the installation here reported, are discussed by B. J. Vincent, Brit. J. appl. Phys. **11**, 132-135, 1960.

[9] Cf., for example, Philips tech. Rev. **19**, 28, 1957/58.

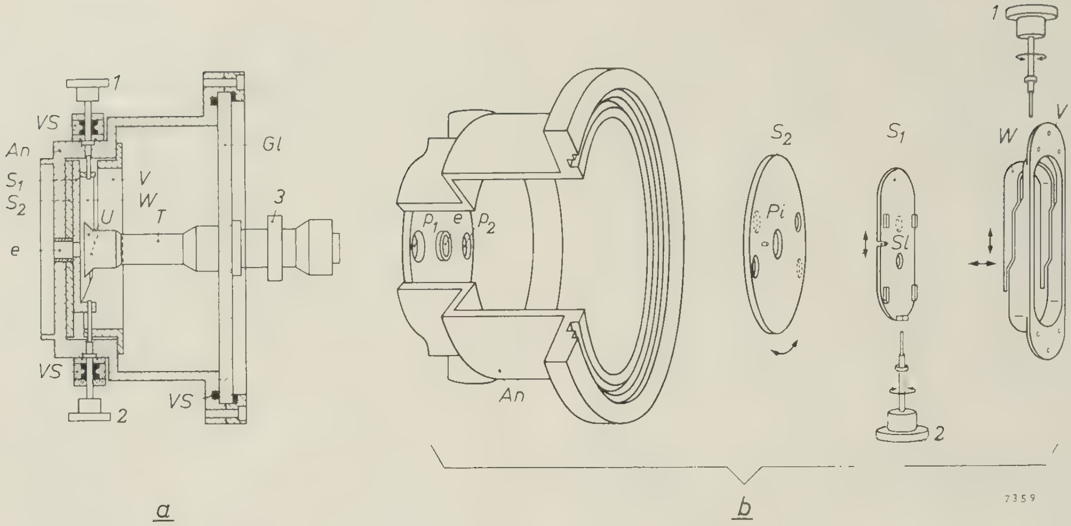

Fig. 18. *a*) Diagram and *b*) exploded view of the vacuum lock between electron gun and the main vacuum system. *U* focussing electrode, guiding the electrons issuing from the cathode (mounted within the support tube *T*) through the hole *e* in the anode *An*. p_1 and p_2 are extra pumping holes. To close *e*, p_1 and p_2, wedge *W* is unclamped by means of knob *1*. By turning knob *2*, plate S_1 is shifted, which causes plate S_2 to rotate by means of pin *Pi* and slot *Sl*. Next S_1 and S_2 are reclamped with *1*. Vacuum sealing is ensured by O-rings (not drawn). *V* clamping bridge piece. *Gl* glass plate carrying the cathode and insulating this from the (earthed) anode. Vacuum seals *VS* are provided for *1*, *2* and *Gl*. Knob *3* is used when replacing the cathode.

mentioned article [3]), normal ignitrons are not really suitable for repetition frequencies of 500 per second. The deionisation time is too long, resulting in ionic bombardment that reduces the life to a fraction of the normal. Sometimes the life amounted to less than 100 hours. The CX 1119 hydrogen thyratron now used has a life that is normal for a valve (i.e. of over 1000 hours). Another advantage is that the thyratron has a lower jitter characteristic than the ignitron. This is of importance if the installation is to be used for stroboscopic radiography.

The electron gun

The electrons to be accelerated are supplied by an electron gun, of which *fig. 18* is a diagram and *fig. 19* a photo. The anode is earthed, as are the corrugated guide and the associated waveguide system. The directly-heated cathode, consisting of a flat spiral of 0.3 mm tungsten wire (*fig. 20*), receives from the modulator the same 50 kV negative voltage pulses as the magnetron cathode. The electrons then attain a velocity of about 0.4 *c* (*c* = velocity of light). A focussing electrode directs the electron beam through a hole in the anode into the corrugated guide.

The exact moment of a cathode failure cannot be predicted and it may therefore occur during the course of making a radiograph. To avoid the necessity of admitting air into the whole evacuated system when replacing the cathode — after which it would take about an hour to re-establish the vacuum — a vacuum lock is incorporated between the electron gun and the main vacuum system. The construction of this lock (fig. 18) is simplified as compared with the previous design [3]). If replacement of the cathode

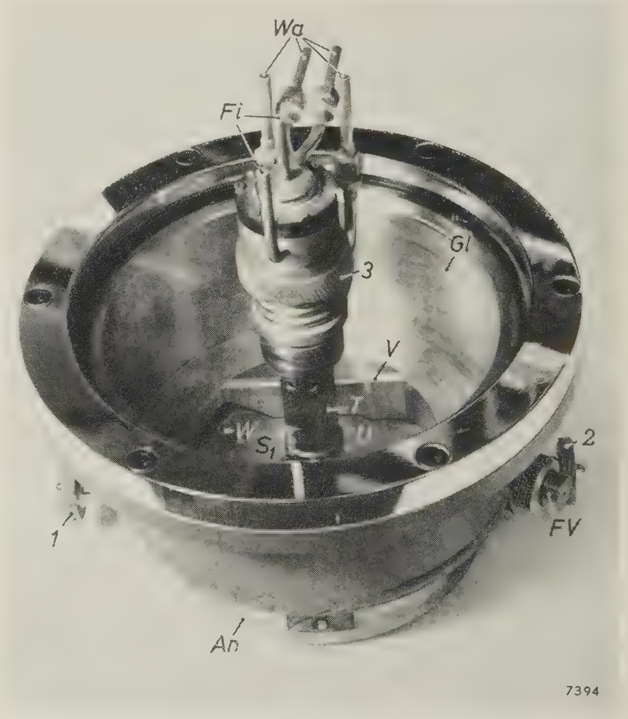

Fig. 19. The electron gun. *Fi* cathode connections. *Wa* connections for water cooling. *FV* connection for backing line. The remaining characters have the same significance as in fig.18.

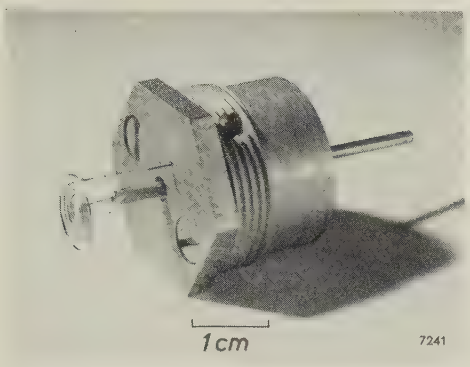

Fig. 20. Cathode holder with the directly-heated cathode of the electron gun. If the cathode has to be replaced, the complete component illustrated here is exchanged. After replacement the new cathode will then automatically be mounted in the correct position.

is necessary, the vacuum lock is closed, and air admitted to the electron gun. By unscrewing a knurled knob *3* the cathode assembly may then be withdrawn. A new pre-focussed cathode unit (fig. 20) having been screwed into position, the electron gun lock is first evacuated to the pressure of the backing pump by means of the special branch of the backing line mentioned on page 203. Connection is then re-established with the high vacuum; owing to the negligible volume of the lock relative to the volume of the accelerator proper, the high vacuum is virtually unaffected. Replacement of the cathode need only interrupt the working of the accelerator for five minutes or less.

The filament current for the cathode is supplied by a 10V-2A mains transformer (visible in fig. 22), with a secondary whose insulation can withstand 50 kV with respect to earth, and whose capacitance to earth is very low (15 pF). This capacitance must be small to limit the rise time of the pulses.

The cathode temperature, and thus the beam current, is controlled by means of a variable autotransformer in the primary of the filament transformer. This autotransformer is accommodated on the control desk.

Rectangular waveguide system

Fig. 21 is a schematic diagram of the accelerator [10]). Of the RF power entering the corrugated guide, part is used for accelerating the electrons, another part is necessary for covering losses, and the remainder is fed back to the entrance of the corrugated guide by way of a feedback bridge. In the present case this remainder amounts to 50%. In the feedback bridge, power from the magnetron makes the total up to 100%. Thus the feedback ratio of the bridge is unity. *Fig. 22* shows the system of rectangular waveguides used for the conduction of the RF power.

The feedback bridge and the waveguides connecting it with the magnetron and with the corrugated guide are filled with air at 2 atm gauge. At the RF powers under consideration, electrical discharges would occur in the guides at atmospheric pressure: either the guides must be evacuated (thus eliminating the need for windows between the waveguide system and the corrugated guide), or they must be pressurised. Pressurising has the advantage that

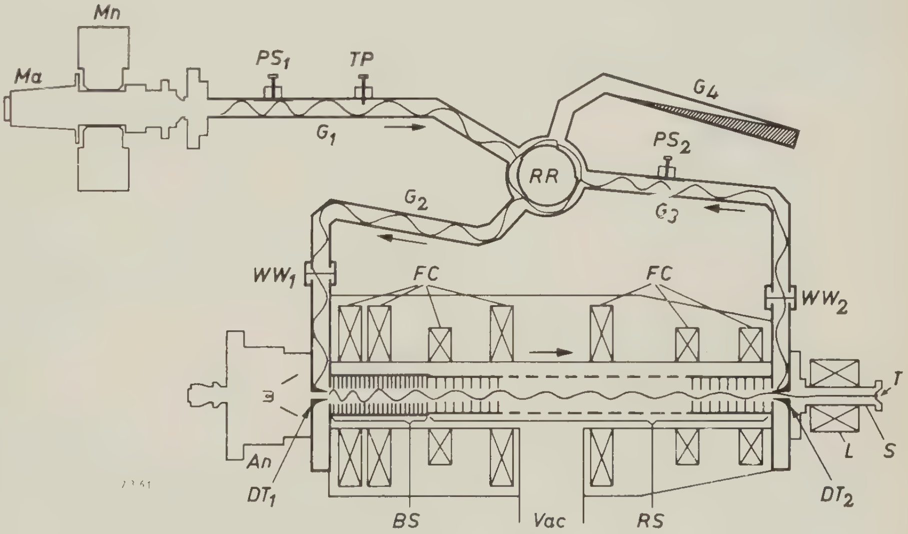

Fig. 21. Diagram of the accelerator. *Ma* magnetron with its permanent magnet *Mn*. PS_2 phase shifter in the rectangular waveguide G_3, serving to ensure correct phasing of the wave arriving at the rat race *RR*, which acts as a feedback bridge. PS_1 tuning phase shifter and *TP* tuning probe for trimming the magnetron frequency. G_4 fourth arm of the rat race, fitted with a matched water load. *BS* and *RS* are respectively the bunching section and the relativistic section of the corrugated guide. Waveguide windows WW_1 and WW_2 separate the vacuum in the corrugated guide from the 2 atm gauge pressure in the remaining rectangular guide system. *An* anode. *FC* coils supplying an axial magnetic field that precludes divergence of the electron beam. DT_1 and DT_2 are respectively the in- and output doorknob transformers [10]). *Vac* connection to the vacuum pump. *S* target snout carrying the system *L* of two magnetic quadrupole lenses that focus the electron beam on the target *T*.

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[10]) The principle of the linear accelerator is discussed by D. W. Fry, The linear electron accelerator, Philips tech. Rev. **14**, 1-12, 1952/53. The transformers DT_1 and DT_2 are discussed on p. 8 of this article. For a recent survey, reference is made to: L. Smith, Linear accelerators, Encyclopedia of Physics, Vol. **44**^{1} (Nuclear Instrumentation), 341-389, Springer, Berlin 1959.

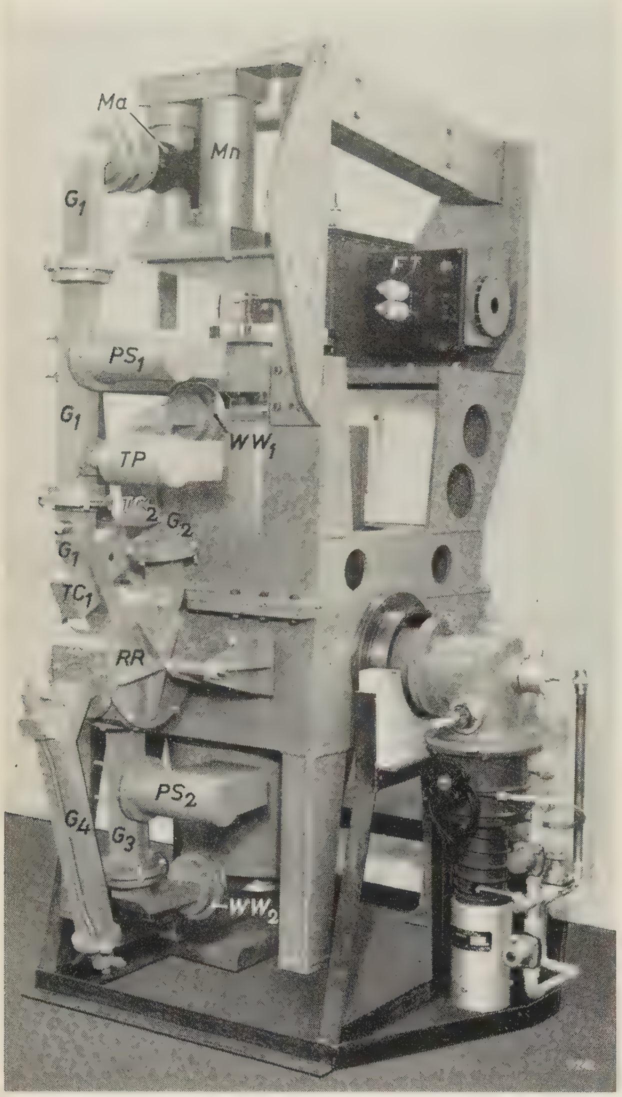

Fig. 22. Photograph of a partly-assembled accelerator, giving a view of the system of rectangular waveguides. TC_1 and TC_2 are thermocouples that measure the RF power 11). *FT* is the mains transformer for the cathode filament. The remaining letters have the same significance as in fig. 21.

sealing problems are less troublesome and that removal of the magnetron does not affect the vacuum in the corrugated guide. Furthermore pressurising is more reliable: it has happened in waveguide systems working under vacuum conditions that the magnetron window has been melted by a glow discharge at this part of the waveguide, remote from the pump, where the vacuum is poorest.

That in the 15 MeV accelerator described earlier 3) evacuation was chosen was due to the fact that at that time no suitable waveguide windows were available for separating the pressurised part from the vacuum in the corrugated guide. Such a window has to withstand a pressure of three atmospheres while transmitting high-power microwave signals (for the window in the line leading to the beginning of the waveguide this power may amount to an average of 4 kW, viz. 4 MW peak power with a duty cycle of 10^{-3}). In the meanwhile, however, a simple demountable window has been developed for this purpose (*fig. 23*). It consists of a polished quartz disc 5.5 cm in diameter, mounted in a brass plate 6 mm thick. An O-ring ensures a good seal. To protect this ring from possible radiofrequency heating effects, the periphery of the disc is metal-coated. Matching of the window is achieved by adjusting the internal diameter of the brass plate to suit a given quartz disc. In this way, close tolerance working of the quartz thickness is not required, nor is the diameter of the disc critical, as the O-ring satisfactorily accommodates reasonable variations in this diameter.

The application of a pressure of 2 atm gauge has called for a new design of the phase shifters (fig. 21). In the 15 MeV accelerator the phase shifters each consisted of a ceramic wedge on an adjustable mount on steel pins in the evacuated waveguide. At a pressure of two atmospheres gauge such a wedge was found to give rise to electric discharges. This has been overcome by using a lozenge-shaped body of polystyrene that can be moved on stainless-steel supports. Just as previously, the phase shifters are each provided with a small electric motor to permit remote adjustment. The protective covers over the driving mechanism are visible in fig. 22.

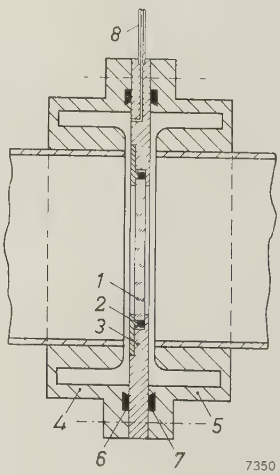

Fig. 23. Cross-section of the waveguide windows (WW_1 and WW_2 in figs 21 and 22). *1* quartz-glass disc mounted in brass flange *3* vacuum-sealed by means of O-ring *2*. *4* and *5* are choke flanges as commonly used in waveguide connections. O-rings *6* and *7* provide vacuum sealing. To the left of the quartz disc the pressure is 2 atm gauge, maintained via the line *8*; to the right is the vacuum of the corrugated guide.

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11) Cf. the article of note 3), page 19.

In the 15 MeV accelerator a "circular magic tee" was used as the feedback bridge; it has been discussed in detail previously [3]). It works successfully but, because the waveguides connected to it do not all lie in the same plane, the construction demands a great deal of space. With a view to manoeuvrability, it was desirable to limit the size of the accelerator as much as possible. A feedback bridge was therefore developed in which the waveguides all lie in one plane. This device is known as a "rat race". This rat race (*fig. 24*) is so constructed that the radio-frequency couplings are separate from the gasketted joints for sealing the device. This construction can also be used in an evacuated system.

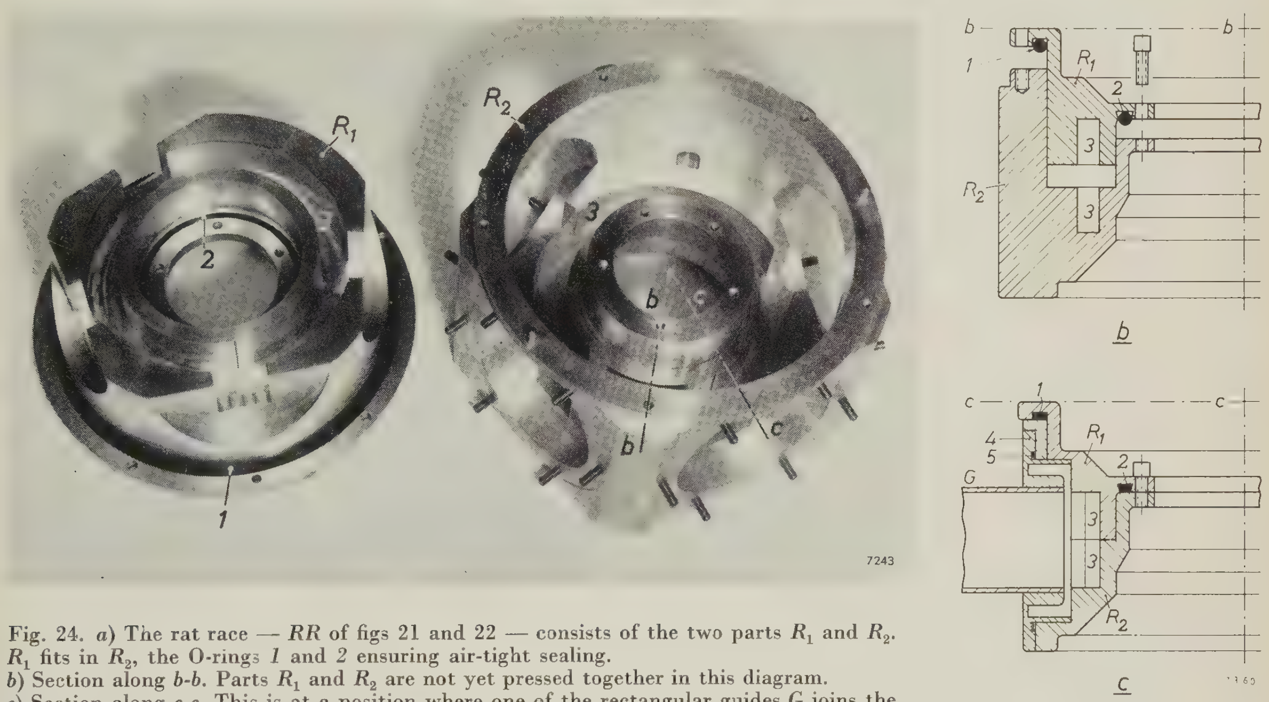


Fig. 24. *a*) The rat race — *RR* of figs 21 and 22 — consists of the two parts R_1 and R_2. R_1 fits in R_2, the O-rings *1* and *2* ensuring air-tight sealing.
b) Section along *b-b*. Parts R_1 and R_2 are not yet pressed together in this diagram.
c) Section along *c-c*. This is at a position where one of the rectangular guides *G* joins the rat-race channel *3*. Parts R_1 and R_2 are fully pressed together in this diagram. For the high-frequency coupling of guide *G* and the rat race a choke flange *4* is used, the O-ring *5* providing the seal.

Corrugated guide

A travelling electromagnetic wave that is to be used for the acceleration of electrons must in the first place have an electrical component in the direction of propagation. In the second place the velocity of the wave in the guide (v_p) must increase in such a way along the guide that the wave and the electrons carried along by it always remain in phase. The electrons enter the corrugated guide with a velocity of about 0.4 *c*. As their energy increases, their velocity increases and approaches *c* asymptotically; v_p must therefore also increase in the same way. An electromagnetic wave with such properties can be obtained in a round copper tube divided by copper diaphragms into separate cells. Such an accelerator tube, commonly called a corrugated guide, is generally used in linear electron accelerators. In the diagram of our accelerator (fig. 21), which is of conventional construction, one can see that the corrugated guide (1 m length, 9 cm external diameter) is surrounded by an envelope 12.5 cm in diameter, to which the vacuum pump is connected and with which all the cells (cavities) are connected by holes. The cavities are thus pumped radially to obtain a good vacuum everywhere. Around the vacuum envelope are the coils supplying the axial magnetic field that precludes divergence of the electron beam. To give mechanical robustness, the whole assembly is encased in a steel drum which also acts as a return path for the magnetic flux.

The way in which v_p increases along the corrugated guide can be controlled by suitably varying the radius *b* of successive cavities (*fig. 25*). The smaller the diaphragm pitch *s*, the more accurately can v_p be made to vary as required. For this reason *s* is made smaller at the beginning of the guide (where v_p must increase quickly) than further along, where the velocity of light has almost been reached. The diaphragms all contribute to the ordinary ohmic losses, so that the number of diaphragms must not be made unnecessarily great.

In the first part of the corrugated guide the electrons that are carried along by the wave are bunched into groups (one bunch per wavelength). The first part is therefore called the "bunching section". The second part is known as the "relativistic section", because the energy here taken up by the electrons mainly results in a relativistic increase of their mass. In the present equipment the corrugated guide consists of a bunching section of 22 cm, with $s = 1$ cm, and a relativistic section — in which the electrons take up by far the greater part of their final energy — of 78 cm with $s = 2$ cm.

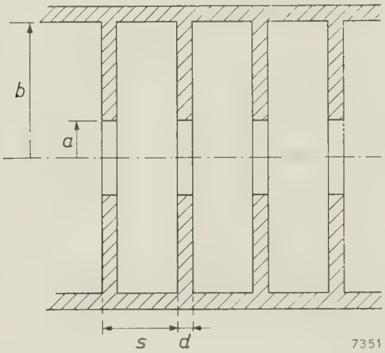


Fig. 25. Dimensions of the corrugated guide sections. a aperture radius. b radius of the resonant cavities. s pitch of the diaphragms. d diaphragm wall thickness.

The parameter a/λ_0

Of great importance is the choice of the radius a of the diaphragm apertures (fig. 25), or, more precisely, of the ratio a/λ_0, where λ_0 is the wavelength in free space corresponding to the frequency f (i.e. $\lambda_0 f = c$). This ratio is the main parameter determining the energy finally taken up by the electrons with a given magnetron power. Once a has been chosen, b is fixed by the specified value of v_p. One would like to make a small, because this results in a high electron energy and hence also in a large X-ray output, because the X-ray output per mA beam current increases sharply with this energy (this can be seen from fig. 26*b*). However, the smaller a, the more sensitive v_p becomes to variations in the magnetron frequency f and to tolerances in the dimensions of the corrugated guide. As the wave and the electrons must be kept very accurately in phase in order to obtain effective operation of the corrugated guide, both dimensional tolerances and constancy of frequency become more and more critical as a is made smaller. The ratio a/λ_0 thus determines the accuracy to be demanded of the frequency and the dimensions. For the corrugated guide of the present equipment, the bunching section has the ratio $a/\lambda_0 = 0.168$, while the relativistic section has the value $a/\lambda_0 = 0.13$. To compensate for the effect on v_p of the discontinuities in a and s at the junction of the two sections, b at this place also shows a discontinuity (fig. 21).

As the electrons gather by far the greater part of their energy in the relativistic section, it is of special importance to have a small value of a/λ_0 in this section.

The selected values of a/λ_0 originate in calculations based on a tolerance of 1 in 10^4 for the frequency and for certain dimensions. Experience since obtained has shown, however, that with these accuracies the value of a/λ_0 for the relativistic section might well have been reduced to 0.1. It would therefore be possible to obtain from a corrugated guide of one metre length a still greater X-ray output than from the present installation. It can be read from fig. 26*c* that about a 30 percent increase of the pulse dose rate can be expected.

Build-up phenomena

In the design of an accelerator, account should be taken of the warming up of the magnetron (effect on frequency) and of the corrugated guide (effect on its dimensions) when the installation is switched on. It is moreover desirable that the frequency is appropriate to the dimensions of the guide not only under steady-state conditions, but also in the warming-up period that precedes it. If this is not so it will be some time after switching on before the full X-ray output is produced. This is known as the build-up effect. Thanks to careful design of the water cooling circuit for the corrugated guide, the full X-ray output is obtained in 2 or 3 seconds.

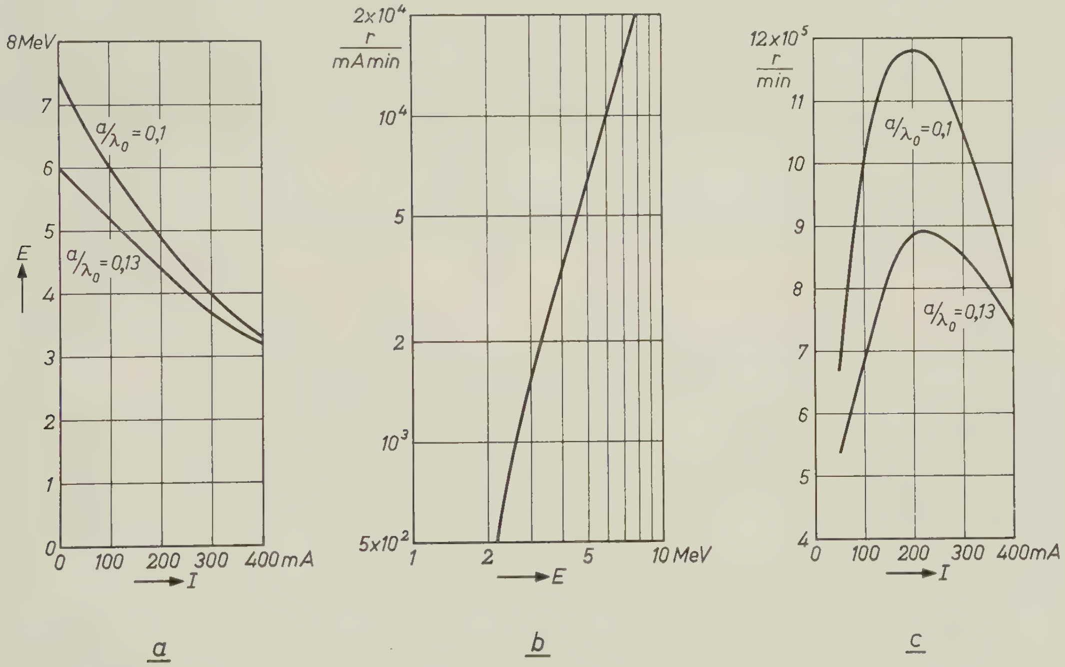
Design for maximum X-ray output

Once the lengths of the bunching and relativistic sections and their values of a/λ_0 have been chosen, and when the magnetron power is given, there remains to decide how v_p, and hence the radius b of successive cavities, must vary along the guide. This variation should of course satisfy the condition that wave and electrons are in phase all along the guide. A suitable variation, however, satisfies this condition only for one value of the beam current. The design of the guide thus depends on the beam current selected. As will be shown, it is possible to estimate theoretically the X-ray output as a function of beam current. A curve is then obtained which shows a maximum and the corrugated guide should obviously be designed for the beam current that corresponds to this maximum.

How the above-mentioned curve is obtained, is shown in *fig. 26*. In fig. 26*a* the energy E of the electrons is plotted as a function of the beam current I, for the case in which the variation in b matches this current [12]). This has been done for two values of a/λ_0 in the relativistic section, viz. $a/\lambda_0 = 0.13$ and $a/\lambda_0 = 0.1$. Every point on such a curve (not measured, but calculated) thus corresponds to a different variation of b, i.e. to a different corrugated guide. In fig. 26*b* the X-ray dose rate per mA of beam current is plotted as a function of the electron energy for a tungsten target. This curve has been obtained from measurements of various workers, including our own measurements. From fig. 26*a* and *b*, fig. 26*c* has been derived, whence it is found that a maximum X-ray output may be expected if a variation of b is chosen that matches the corrugated guide at a beam current of about 0.2 A. It follows from fig. 26*a* that with this beam current an electron energy of about 4.3 MeV may be expected when a relativistic section with $a/\lambda_0 = 0.13$ is used. To find the X-ray dose rate in the beam axis at a distance of 1 m from the target, with no focussing of the electron beam, the value of 8.9×10^5 r/min found from fig. 26*c* still requires to be multiplied by the duty cycle. With 500 pulses of 1.8 μsec per second (see page 206) the duty cycle amounts to 9×10^{-4}, so that 800 r/min may theoretically be expected. The actual accelerator comes very close to these expectations.

As a further illustration of the robustness and versatility of this type of equipment it can be mentioned that a modified version of the equipment described in this article has been supplied by Mullard to the United Kingdom Atomic Energy Authority for use in the radiography on site of nuclear-power-station pressure vessels (*fig. 27*).

The main modification was the elimination of all external water cooling circuits. A further difference was the accommodation of all the power supplies, modulator and switchgear in a weatherproof control cabin (fig. 27*b*) linked to the accelerator by



a b c

Fig. 26. *a*) Calculated energy E attainable by the electrons in a corrugated guide with feedback, if the variation of the radius b (cf. fig. 25) along the guide exactly matches the electron-beam current I. Each point of the curves therefore refers to a different guide. The curves are calculated for guides with a 22 cm long bunching section of 1 cm pitch and $a/\lambda_0 = 0.168$, followed by a 78 cm relativistic section of 2 cm pitch with both $a/\lambda_0 = 0.13$ and $a/\lambda_0 = 0.1$. The electrons enter the guide with a velocity of 0.4 c, the magnetron power is 2 MW (in the pulse), and the feedback ratio is unity.
b) Measured X-ray output as a function of the electron energy in MeV of a parallel electron beam falling perpendicularly on a tungsten target. The curve represents the dose rate on the axis of the generated X-ray beam at 1 m from the target, for a mean electron beam current of 1 mA.
c) Curves obtained by combining the data of *a* and *b*, representing the predicted X-ray intensity from a linear accelerator during a pulse, on the beam axis at 1 m from the target, as a function of the beam current I for which the accelerator is designed. To obtain maximum X-ray output, the accelerator should obviously be designed for $I \approx 200$ mA.

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[12]) The method of calculating these curves is discussed in the article quoted in note [3]), pages 3-4.

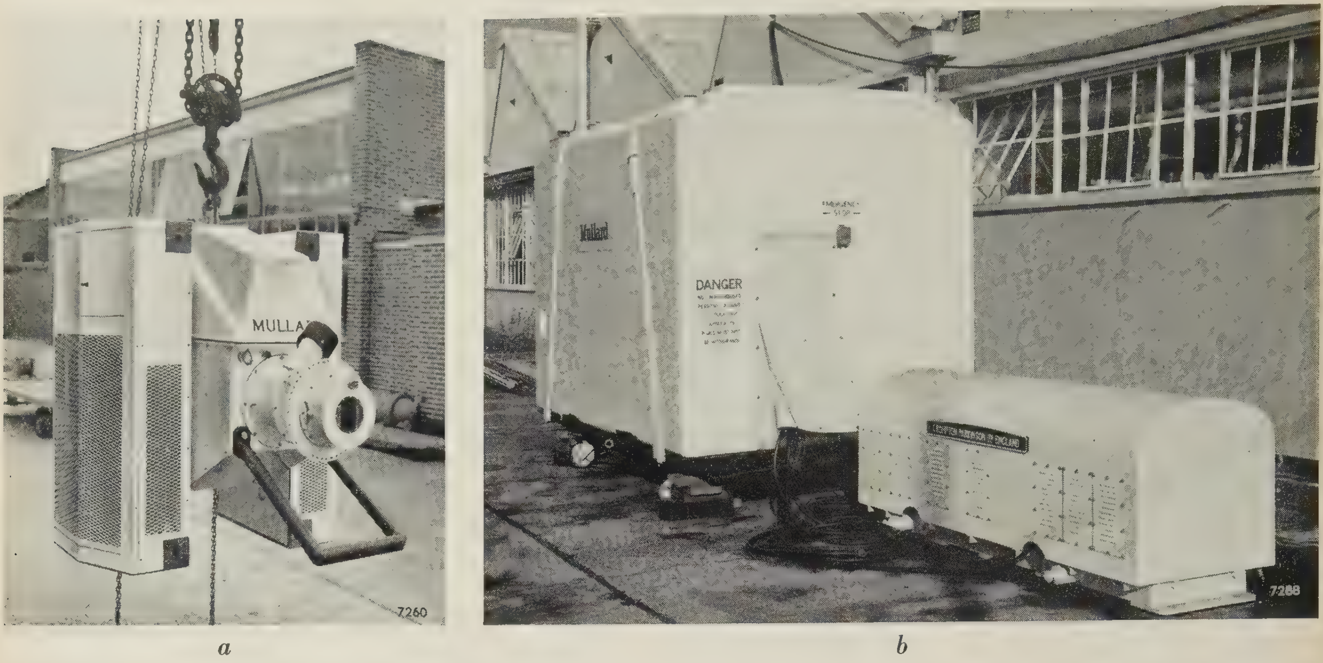

Fig. 27. A fully transportable version of the linear-accelerator radiographic unit. The installation is wholly independent of external electricity and water supplies.
a) The accelerator X-ray generator proper. Suspended from a crane it can be manoeuvred into any desired location.
b) Cabin containing power supplies, control equipment and modulator. Foreground: rotary alternator (for mains stabilisation on building sites where large fluctuations are encountered).

cables 250 feet long. The suspension system described in this article is not needed in the present case: the accelerator can easily be handled and manoeuvred by site cranes in prefabrication shops and behind biological shields. The high output of the accelerator also permits it to be mounted on a turntable at the centre of curvature of the pressure vessel, so minimising setting-up time and allowing considerable lengths of weld to be radiographed at one exposure (*fig. 28*).

Depending upon the type of film used, it has been reported that up to 10 feet of pressure-vessel weld

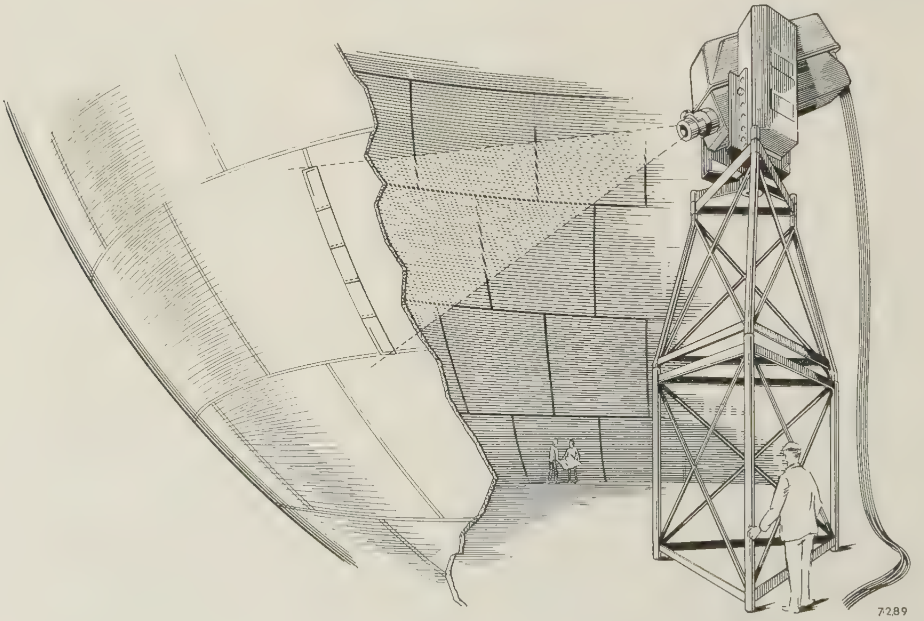

Fig. 28. Sketch of the transportable unit set up at the centre of a spherical steel reactor pressure vessel (diameter 20 yards, wall thickness $3\frac{1}{2}''$, or 9 cm). Such pressure vessels, used in nuclear-reactor power stations, are constructed on site and radiographed during construction.

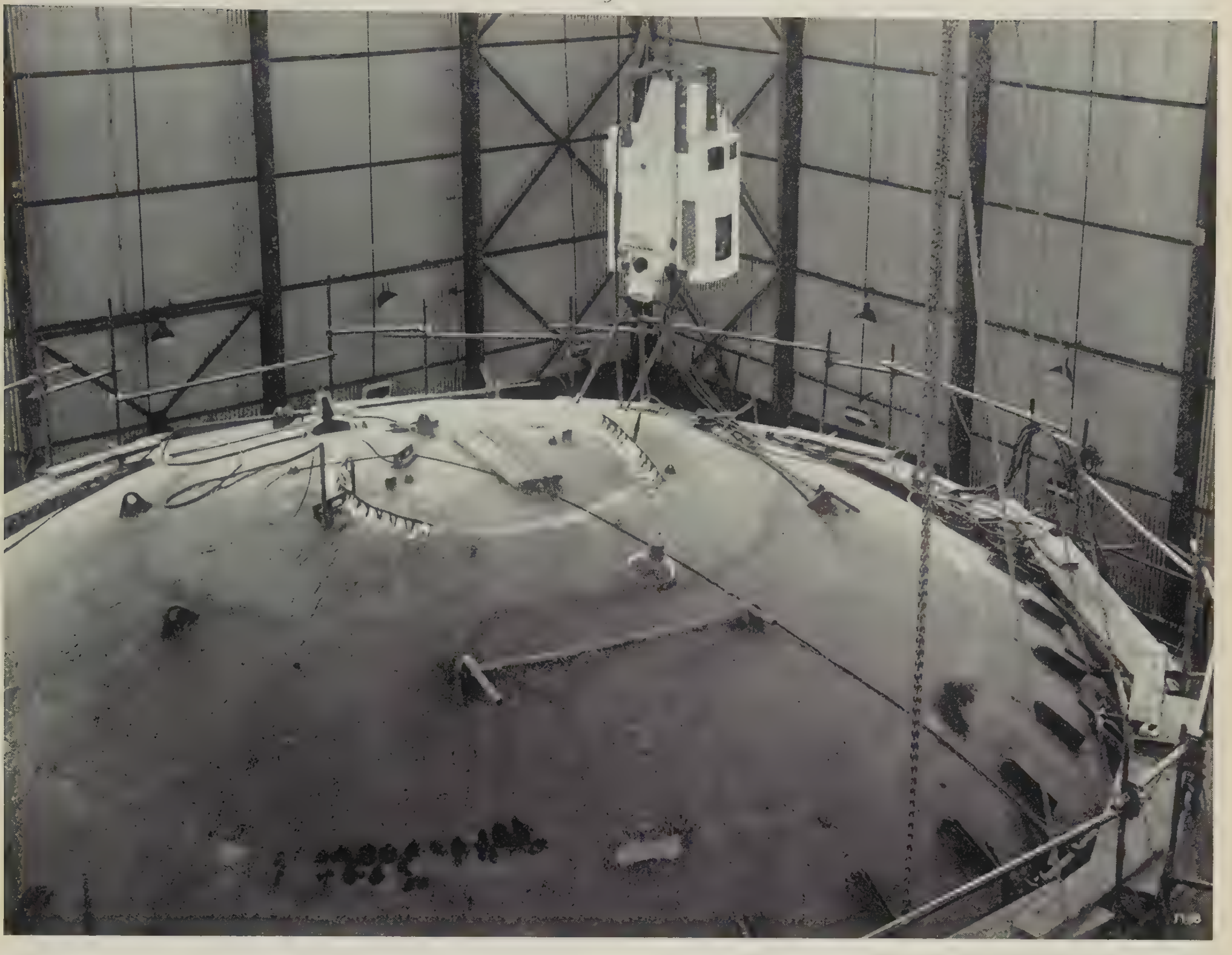

Fig. 29. The transportable accelerator in operation. It is shown here above one of the pressure vessels of the nuclear power station at Trawsfynydd (Wales). Photograph by courtesy and with permission of Atomic Power Constructions Ltd.

can be radiographed in 15 minutes. *Fig. 29* shows the accelerator in operation, suspended above a reactor pressure vessel. The reduced radiographic schedule on projects of this type represents a very considerable economic advantage over all other known radiographic equipments suited to applications of this character.

The author wishes to thank the Director of Mullard Research Laboratories for permission to publish this article. He also wishes to thank the staff of the Armaments Research and Development Establishment and his colleagues at Mullard Research Laboratories for their invaluable cooperation and assistance.

Summary. With an electron linear accelerator, based on a corrugated waveguide of 1 m length, it is possible to construct a very intensive source of hard X-rays that is particularly suitable for the radiography of heavy steel sections (up to 16″). An X-ray installation for such purposes, in regular use since 1956, has been designed and constructed by Mullard Research Laboratories in England. Easy manoeuvrability of the X-ray beam is a special requirement of such industrial radiographic equipment in view of the unwieldiness and weight of many specimens. This has been achieved by means of a suspension which permits of swiveling and tilting and of varying the height of the accelerator. The accelerator is mounted under a trolley riding on a gantry, rather like a gantry crane. The electrons are accelerated to 4.3 MeV and focussed to a spot of 1.5×0.5 mm on a tungsten target by means of a system of magnetic quadrupole lenses. The X-ray output is variable in steps; the maximum dose rate at 1 m from the target amounts to 600 r/min in the centre of the X-ray beam. A specially developed X-ray head limits the beam to a rectangular field whose dimensions at 1 m from the tungsten target are adjustable to between 3×3 cm and 15×25 cm. Results depend on radiographic technique; on the average one may expect to detect flaws of about 0·75 mm in a 30 cm (1 foot) wall, when using a slow, sensitive film.

Various details of the design are described: the rotatable joints in the high-vacuum and the backing lines, enabling the oil-diffusion pump to remain vertical when the accelerator is tilted; the electron gun with its simplified vacuum lock, between it and the high vacuum of the corrugated guide, which permits cathode replacement in less than five minutes; the air-tight waveguide windows, enabling the system of rectangular waveguides — that couples the magnetron (the high-frequency energy source) to the corrugated guide — to sustain a pressure of 2 atm gauge; the "rat race" serving as a feedback bridge and providing a compact construction. The design of the corrugated guide for maximum X-ray output is explained.

At the end of the article brief mention is made of a more recent X-ray unit of this type, also with a 4.3 MeV linear accelerator, that is fully transportable. This version has proved of great value in the construction of pressure vessels for nuclear reactors.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of those papers not marked with an asterisk * can be obtained free of charge upon application to Philips' Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2, where a limited number of reprints are available for distribution.

2875: Th. P. J. Botden: The silica gel leak detector (Advances in vacuum science and technology, Proc. 1st int. congress on vacuum techniques, Namur, Belgium, June 1958, editor E. Thomas, Vol. 1, pp. 241-244, Pergamon, Oxford 1960).

The silica-gel leak detector consists of a sensitive Penning ionization gauge connected to a tube filled with grains of silica gel, the latter at liquid-air temperature. For a flow of H_2, He and Ne through the silica gel, the sorption is less than 5%, while for air only the fraction 3×10^{-4} can pass the silica gel. Because of this selective sorption and the use of the Penning gauge, leaks of 10^{-9} Torr l/s can be readily detected. With some precautions it is possible to detect leaks of 10^{-11} to 10^{-12} Torr l/s. The sensitivity is equal for H_2, He and Ne when these gases are used as detection gas. An indication of a leak is, in general, obtained within 10 s. From the plot of gauge current versus rate of leak and the sensitivity curve of the gauge, the approximate values of pumping speed of the gauge for H_2, He and Ne have been calculated.

2876: N. Warmoltz: Spectromètre de masse pour la détection des fuites, fonctionnant avec un mélange à faible teneur en hélium (as **2875**, Vol. 1, pp. 257-259). (Mass spectrograph for leak detection, using a mixture of helium and air; in French.)

Description of a leak detector using helium as detector gas. The presence of He is demonstrated with a simple mass spectrograph. The ions, drawn from a hot-cathode source, are initially accelerated by an electrostatic lens and focussed on the first dynode of a photomultiplier tube, which gives considerable amplification of the ion current to be measured. If the air pressure in the apparatus is fairly high, the peaks at 6 (C^{++}), 7 (N^{++}) and 8 (O^{++}) may overlap the peak at 4 (He^{+}). This is avoided by using a double spectrograph (analogous with a double monochromator). The multiplier tube increases the sensitivity by a factor of 500. This makes it possible to use a mixture of helium and air with only 1-5% helium, which is much more economical.

2877: J. J. Opstelten and N. Warmoltz: Un manomètre à membrane à échelle linéaire pour des pressions entre 10^{-5} et 10 mm Hg (as **2875**, Vol. 1, pp. 295-298). (A linear-scale diaphragm manometer for pressures between 10^{-5} and 10 mm Hg; in French.)

The essential part of the manometer described is a stainless-steel diaphragm 20 μ thick. The bending of the diaphragm is a function of the pressure drop across it, and is measured electrically. For this purpose the diaphragm is sandwiched between two metal plates mounted at a distance of 25 μ on either side, with ceramic spacers and glass lead-in insulators. The two capacitors thus produced are incorporated in a Wheatstone bridge with AC supply (frequency 0.5 Mc/s). A null method of measurement is used: two voltages, $V + v$ and $V - v$ respectively, are applied to the two capacitors and v is varied so as to bring the diaphragm into the balanced position. The pressure on one side is kept constant at about 10^{-7} mm Hg with a Penning gauge. A linear relation then exists between v and the pressure on the other side. The choice of V depends on the pressure to be measured in a range from 10^{-5} mm Hg to 1 mm Hg, beyond which a troublesome gas discharge occurs. Higher pressures can be measured by omitting V and determining the capacitance of one of the capacitors in a bridge. This extends the range up to 10 to 20 mm Hg. The manometer can if necessary be heated up to 150 °C. A special circuit is needed for gases that form absorbed layers on the capacitor plates. In the case of highly reactive gases (e.g. UF_6) the chamber to which the gas is admitted is not provided with an electrode, so that the ceramic and glass parts (which are the most liable to attack) can also be omitted.

2878: S. Woldring: The mechanics of breathing — general principles and technique of measurement (Proc. Tuberculosis Res. Council (Roy. Netherl. Tuberculosis Ass.) No. 46, 1959, pp. 5-27, published 1960).

A survey is given of the basic principles of the mechanics of lung ventilation. Lung volume, rate of flow and intrathoracic pressure are shown to be interrelated and to depend on the elastic properties of the lungs and on the resistance to flow of the airways. The factors which determine the behaviour of these quantities are discussed.

An instrumental set-up is described for the simultaneous recording of volume, pressure and flow. It also enables the investigator to plot these variables against each other or against time. The characteristic properties of these instruments are discussed.

2879: H. C. Burger: The significance of the flow/volume diagram in the study of the mechanics of breathing (as **2878**, pp. 28-47).

Using examples of normal and abnormal cases, the author demonstrates the diagnostic value of flow-volume diagrams, as recorded by the equipment described by Woldring in No. **2878** above. Some of the phenomena observed are attributed to the fact that the respiratory passages during rapid exhalation may become constricted or almost closed by a check-valve mechanism. An aerodynamic explanation is given to supplement the mechanical theory.

2880: G. D. Rieck and H. A. C. M. Bruning: Subcrystals in large vapour-grown crystals of tungsten (Acta metallurgica **8**, 97-104, 1960, No. 2).

Single crystals of tungsten, grown by decomposition of the chloride in the vapour phase, were investigated. A substructure has been found both with X-ray and microscopic techniques. The disorientation between the subcrystals is random and is therefore different from that found in single crystals in recrystallized doped tungsten wires. The occurrence of a substructure or even dendritic branches depends upon the circumstances during the growth. The rows of etch pits on the photomicrographs of etched surfaces are of the same nature as those found by other authors on tungsten prepared in a different manner. Electron-microscope pictures of etched surfaces sometimes reveal pyramid-shaped etch hills and whisker-like needles, which are supposed to be subcrystals grown with the highest perfection, during temporarily favourable conditions.

2881: P. Westerhof and E. H. Reerink: Investigations on sterols, XV. The syntheses and properties of $9\beta,10\alpha$-progesterone and 6-dehydro-$9\beta,10\alpha$-progesterone (Rec. Trav. chim. Pays-Bas **79**, 771-783, 1960, No. 7).

The preparation of steroid hormone analogues with abnormal configuration has been intensively investigated. This paper describes the synthesis of $9\beta,10\alpha$-progesterone and 6-dehydro-$9\beta,10\alpha$-progesterone from lumisterol$_2$. Both compounds show a pronounced progestational activity, even when administered orally. Numerous intermediates are described too. The structures of the compounds prepared were confirmed by ultraviolet and infrared absorption data. The biochemical activities are recorded briefly, and will be reported fully elsewhere.

2882: P. Westerhof and E. H. Reerink: Investigations on sterols, XVI. The syntheses and properties of $9\beta,10\alpha$-androstanes (Rec. Trav. chim. Pays-Bas **79**, 794-806, 1960, No. 7).

Pursuing the investigations described in No. **2881**, the authors describe the syntheses of a number of $9\beta,10\alpha$-androstanes, starting from 22-(1′-piperidyl)-$9\beta,10\alpha$-bisnorchola-4,20(22)-dien-3-one or from $9\beta,10\alpha$-bisnorchol-4-en-3-on-22-al. The physiological properties of the $9\beta,10\alpha$-androstanes prepared will be reported elsewhere. The paper closes with a detailed description of the methods of preparation. The chemical structures assumed for the compounds are confirmed by absorption and optical-rotation data.

2883: B. G. van den Bos, M. J. Koopmans and H. O. Huisman: Investigations on pesticidal phosphorus compounds, I. Fungicides, insecticides and acaricides derived from 3-amino-1,2,4-triazole (Rec. Trav. chim. Pays-Bas **79**, 807-822, 1960, No. 7).

The preparation and the biological properties of a number of compounds with fungicidal, insecticidal and acaricidal activities are described. The compounds were prepared by substitution of a phosphorus-containing group for a hydrogen atom of the 1,2,4-triazole nucleus in 3-amino-1,2,4-triazole or a 5-substituted derivative thereof. Biological activity was highest when the phosphorus-containing group was a bis(dimethylamido)phosphoryl group.

2884: A. H. Boerdijk: Diagrams representing states of operation of a general thermocouple (J. appl. Phys. **31**, 1141-1144, 1960, No. 7).

The state of operation of a thermocouple of which (*a*) the bars have an arbitrary shape, (*b*) the properties of the materials are arbitrary functions of temperature, and (*c*) the composition is, under certain restrictions, inhomogeneous and anisotropic, depends on three independent parameters: the current I and the temperatures T_1, T_2 of the junctions. If T_2 is kept constant, operating characteristics, such as curves of constant output power or efficiency, can be plotted in an $I,(T_2—T_1)$ diagram. The existence of regions of generation of electricity and of cooling is proved. These regions are investigated. Possible generalization and reduction of the diagram are discussed. As an illustrative example, the cooling region of a general couple with temperature-independent properties is dealt with.

2885: J. W. L. Köhler: The gas refrigerating machine and its position in cryogenic technique (Progress in Cryogenics **2**, 41-67, 1960).

After a brief review of the various cryogenic techniques, the theory of the Stirling process is described. The ideal cycle (without losses) and the departures from the ideal in practical cycles are discussed, and an example is given. Applications mentioned are the liquefaction of air, gas separation, the cold box, etc. The position of the gas refrigerating machine is considered in relation to existing refrigerating methods, in which connection the subject of efficiency is discussed. It is shown that the Stirling process has opened up many new possibilities in the cryogenic field, especially in the range between —80 °C and —180 °C. This applies in particular to small gas refrigerating machines, although the refrigerating capacity varies in a wide range and at present an upper limit is not in sight. See also Philips tech. Rev. **16**, 69 and 105, 1954/55, and **20**, 177, 1958/59.

2886: G. J. M. Ahsmann and Z. van Gelder: La chute cathodique normale pour des cathodes monocristallines (Le Vide **15**, 226-233, 1960, No. 87). (The normal cathode drop in the case of monocrystalline cathodes; in French and in German.)

The authors describe reproducible measurements of the normal cathode drop in the case of monocrystalline platelets of germanium, silicon and copper in neon at a pressure of 40 mm Hg, using the sputtering method. Changes in the surface sometimes give rise to changes in the cathode drop. Differences between crystal faces are attributed to differences in work function φ. The formula $V_n = C\varphi$ is discussed. Also dealt with are temperature effects due to (*a*) changes in density distribution, and (*b*) surface changes brought about by the penetration of gas ions. Monocrystalline materials, because of their stable and reproducible cathode drop, are in principle well-suited for the production of glow-discharge stabilizers.

2887: A. Kats and Y. Haven: Infra-red absorption bands in α-quartz in the 3 μ region (Phys. Chem. Glasses **1**, 99-102, 1960, No. 3).

In quartz crystals, H^+ ions occur as impurities. The most common impurity is Al^{3+}, which replaces Si^{4+}; the resultant charge deficiency is compensated by Li^+, Na^+ or H^+. The presence of the H^+ ions gives rise to absorption bands at 3311, 3371 and 3435 cm^{-1}. It is shown from deuterium exchange experiments that some bands in this part of the absorption spectrum are due to O-H vibrations. The exchange is effected by heating quartz crystals at 1000 °C in D_2O vapour. The absorption referred to then disappears and new O-D bands appear in the region of 2500 cm^{-1}.

2888: L. Heijne: Photoconductive properties of lead-oxide layers (thesis Amsterdam, June 1960).

In this thesis a study is made of the photoelectrical properties of vapour-deposited polycrystalline layers of very pure PbO in the yellow, orthorhombic modification. These layers can be heated to about 350 °C without phase change, unlike single crystals, which have a tendency to change to the red, tetragonal modification, which is stable below 489 °C. Special attention is paid to the properties of semiconductor contacts, in connection with the space-charge layers associated with them. The mathematical analysis of the flow of charge carriers and the kinetics of their generation and recombination is presented. The methods of preparation and measurement are described and experimental results are given. A separate study is devoted to trapping levels and the determination of their properties using the electrical glow-curve method. The last chapters deal with the effect of impurities on the photoelectrical characteristics, and discuss the use of photoconductive layers in television camera tubes.

2889: N. V. Franssen: Some considerations on the mechanism of directional hearing (thesis Delft, July 1960).

This thesis deals with problems of directional hearing in connection with stereophonic sound reproduction. Like recent investigations by Cherry, Licklider and David, it is concerned with the mechanism of directional hearing as well as with observable phenomena. An attempt is made to design and build an electronic model of the hearing mechanism capable of explaining the experiments, whose purpose, among other things, is to give a clearer insight into the concepts of intensity and time differences. It is shown that the apparent direction of the sound is mainly determined at the start. The behaviour of the model is in reasonably good agreement with measurements made by K. de Boer. The experiments indicate that front-back discrimination is mainly achieved by movements of the head as far as low tones are concerned, whereas the influence of the external ears predominates for high tones. The relation between head movements and the projection of the perceived signals in space is discussed. Experiments relating to the discrimination of binaurally presented frequency differences are described. The results are explained in terms of a second electronic model. The combination of this model with the earlier one makes it possible to give a plausible explanation of the phenomena produced when two loudspeakers emit speech or music with a relatively large time difference. In the last chapter it is shown that the model can also cast some light on hearing phenomena not directly related to direction. This is discussed with respect to the reception of pitch and timbre. A possible mechanism for the analysis of sound by the hearing is considered, and the physical quantities related to the subjective evaluation of a given sound are suggested.

2890: W. Verweij: Probe measurements and determination of electron mobility in the positive column of low-pressure mercury-argon discharges (thesis Utrecht, September 1960).

This thesis describes measurements and calculations relating to the positive column of electrical discharges in mixtures of argon and mercury vapour. The investigation was particularly concerned with the electrical properties of the plasma, which are mainly determined by the mobility of the electrons. Using electric probes, the electron concentration and its radial distribution, the electron temperature and the field strength (gradient) along the axis were measured for numerous current values and partial pressures of argon and mercury vapour. From the probe characteristics, obtained as described by Langmuir, it was possible to determine the concentration and the velocity distribution of the electrons in the plasma. Measurements with radially displaceable probes provided the spacial distribution of these data. The field strength was determined with two probes located at a known distance from each other on the tube axis. Reliable and reproducible results were ensured by taking steps to avoid oscillations at the electrodes, by using very thin and short probes (20 μ thick, and a few mm long), and by heating the probes before each measurement. In each series of measurements one variable was changed and the others held constant. The argon pressure was varied from 0 to 20 mm Hg, the mercury-vapour pressure from about 0.5×10^{-3} to 90×10^{-3} mm Hg. The current varied from 0 to 800 mA. The velocity distribution of the electrons could be characterized by an electron temperature. Two methods of determining electron concentration gave values in good agreement with one another for argon pressures below about 9 mm Hg. The experimental temperature values of electron mobility were reduced to the case of a homogeneously distributed gas filling. It is shown that the electron mobility in the gas mixture can be satisfactorily calculated from the collision cross-sections of the gas atoms according to the Lorentz electron theory, but not from the mobility values in the separate components.

2891: E. F. de Haan: Signal-to-noise ratio of image devices (Adv. in Electronics and Electron Physics **12**, 291-306, 1960).

After giving the general formulae for noise in induced currents and noise sources in television, the author analyses the noise in various image devices, i.e. in image intensifiers (for X-rays and light) and in multiplier tubes. He then discusses methods by which the signal-to-noise ratio S/R can be improved. Finally, it is shown how these methods can be applied to pick-up equipment using vidicons and image orthicons. A distinction is made between noise where S/R is proportional to the square root of the radiation intensity, and where S/R increases linearly with the radiation intensity.

2892: W. Kwestroo and A. Roos: Compounds in the system TiO_2-Cr_2O_3-Fe_2O_3 (J. inorg. nucl. Chem. **13**, 325-326, 1960, No. 3/4).

The three-phase system TiO_2-Cr_2O_3-Fe_2O_3 was investigated by firing various mixtures of these oxides at 1300 °C and quenching them to room temperature. Some of the compounds, which Andersson found in the two-phase system TiO_2-Cr_2O_3, were examined as regards their stability in the presence of Fe_2O_3. It is shown that the compound $TiCr_2O_5$, which was not found by Andersson, can be made by replacing at least a sixth part of the Cr^{3+} ions by Fe^{3+} ions. The structure of this compound is discussed.

2893: R. J. Meijer: The Philips Stirling thermal engine — analysis of the rhombic drive mechanism and efficiency measurements (thesis Delft, November 1960).

This thesis is devoted to the Philips hot-gas engine with rhombic drive mechanism. Chapter I contains a short history of the hot-gas engine, and discusses the Stirling process and a new drive mechanism for the displacer-piston engine which offers great advantages for balancing the engine and reducing the gas forces. Chapter II contains the analysis of this "rhombic drive", viz. the derivation of the conditions for balancing; the derivation of various quantities needed for further calculations from the dimensions of the drive mechanism; the calculation of the pressure variations in the common buffer space of a multi-cylinder engine with arbitrarily chosen crank angles; the calculation of the torque due to gas forces and inertia forces; the calculation of the forces in the drive mechanism; an estimation of the friction energy and the torque due to friction. Some applications of the equations involving the torque are also given. This chapter ends with a sample calculation for a single-cylinder hot-gas engine which has been built and tested in the Research Laboratories, Eindhoven. Chapter III describes efficiency measurements made on the test engine mentioned in chapter II. After a short description of the construction of the engine the measuring equipment is described; the measurements are summarized in tables and graphs. Finally, some properties of the hot-gas engine are compared with those of the internal-combustion piston engine. The equations derived in this thesis are collected in an appendix; three further appendices give the coefficients of the series expansions used in the calculations of chapter II. See also Philips tech. Rev. **20**, 245, 1958/59.

2894: C. A. de Bock and A. M. Worst-Van Dam: A method for the measurement of antibodies against *Hemophilus pertussis* in sera (Antonie van Leeuwenhoek **26**, 73-76, 1960, No. 1).

The antibody content of *Hemophilus pertussis* sera is usually determined with the tube-agglutination technique, wherein the agglutinogen consists of a fresh *H. pertussis* phase I bacteria suspension, prepared from a culture on the well-known Bordet-Gengou agar. The authors frequently needed such a fresh suspension in order to determine agglutination titers from sera. As the preparation of such fresh suspensions takes up much time, they decided to search for a stable *H. pertussis* antigen, with the same properties as a fresh bacterial suspension. To obtain a further saving of time, a modification of the usual technique of tube-agglutination was desirable. For the purpose the method with porcelain tiles known from the field of virology was adapted.

In the present paper the preparation of coloured *H. pertussis* antigen and a new agglutination technique are described and their usefulness is shown.

2895: C. A. de Bock and A. M. Worst-Van Dam: Fixation of the agglutinogen from *Hemophilus pertussis* on the bacterial surface (Antonie van Leeuwenhoek **26**, 126-128, 1960, No. 1).

In the preparation of an antigen from *Hemophilus pertussis* (see No. **2894**) it was found that with some methods the agglutinogen is almost lost from the bacterial surface. Further investigation showed that the agglutinogen is rather soluble in some suspending media but can be fixed on the bacterial surface with formaldehyde in saline.

Now available

T. J. Kroes: Tube and semiconductor selection guide 1960/61, Philips Technical Library, 157 pp.

This book, now available in the third, revised edition, is compiled with the aim of helping the user to find, among the many thousands of types of tubes and semiconductors, the type that is best suited for the purpose he has in mind. It will also be useful to the dealer who has to plan or extend his stocks, and who wants to limit the number of different types as much as possible. The book contains an extensive "interchangeability and replacement list" (50 pp.) i.e. a list of tubes and semiconductors together with the equivalent or nearly equivalent Philips types. Further details are tabulated in seven sections: Tubes for receivers and amplifiers; Cathode-ray tubes; Transmitting tubes; Tubes for microwave equipment; Industrial tubes; Miscellaneous; Semiconductors.

The text accompanying the tables is in English. The book begins with an alphabetical list of the terms used, with their translations in French, German and Spanish, and explanatory introductions in many languages.

K. Hinkel: Magnetrons, Philips Technical Library, 1961, 93 pp., 55 figures.

Experience has shown that many people who work with magnetrons and microwaves have only a vague idea of how these tubes work, and all the uses to which they can be put. This book has been written to explain the operation of these tubes to such people, and to set out the physical principles on which the operation is based. The book is also suitable for students. The six chapters are entitled: Introduction; The electrical mechanism; The circuit; Conditions for oscillation; Examples of practical delay lines and cathodes; The characteristics of magnetrons.

Spanish, German and French editions of this book will also appear.